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FOR SYSTEM RELIABILITY

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## ABSTRACT

The basic problem of determining objective (frequentistic) confidence bounds for the reliability of a series system based on failure data from tests of the independent components is addressed. The notion of confidence bounds based on orderings imposed on the sample space is exploited, and certain optimality considerations are incorporated. Advantage is taken of the simplifications resulting from the use of the Poisson approximation for data from highly reliable components. Tables of exact confidence bounds are produced for the case of two-component systems. These bounds are computed using sample orderings generated sequentially by a two-stage, prospective optimization procedure. A generalization of the Lindstrom-Madden technique is proposed for using the tables to find confidence bounds for systems consisting of more than two components with differing sample sizes.

Key Words: Reliability, series-system, confidence bounds, Poisson approximation, Lindstrom-Madden, sample orderings.

# FEASIBLE OBJECTIVE CONFIDENCE BOUNDS FOR SYSTEM RELIABILITY

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## 1. Introduction

Certainly one of the most basic statistical problems in the assessment of system reliability is that of determining a confidence bound on the reliability of a series system based on component failure data. The continuing appearance of papers concerned with this subject (e.g., Harris and Soms 1981, Butcher et al. 1978, and Winterbottom 1980) testifies to the elusiveness of solutions which are both practically feasible and acceptably precise. The present paper deals with the case of systems characterized by high intrinsic reliability ( $>90\%$ ) where the use of the Poisson approximation for the binomial distributions of component failure data does not introduce appreciable error. The emphasis is on objective, frequentistic confidence bounds which avoid the uncertainties of interpretation associated with posterior bounds obtained by Bayesian methods. The use of the Poisson distribution provides several advantages. It easily leads to valid results for cases involving zero observed failures for some components where maximum likelihood methods and other proposed approximations tend to break down (see, e.g., Madansky 1965 and Mann et al. 1974). It also permits the pooling of failure data for different components having the same test sample sizes. This potential reduction in the effective number of system components enhances the utility of tabulated bounds such as those presented here.

Because of the structure of the problem, universally optimal confidence bounds for system reliability (i.e., "uniformly most accurate" bounds in the sense of Lehmann 1959) do not generally exist. On the other hand, the ideas of Buehler (1957) may be exploited to produce a variety of valid confidence bounds based on total orderings of the sample points. Such bounds are exact in the sense that the desired coverage probability is guaranteed. The construction of good confidence bounds is thus reduced to the selection of suitable orderings imposed on the sample space. This is the approach adopted in the present study. Previous applications of these methods to reliability may be found, for example, in Harris and Soms (1980), Johnson (1969), and Lipow and Riley (1959).

Once the sample ordering approach has been chosen, there remains the problem of determining orderings which lead to confidence bounds which are "good" according to some criterion measuring the size (length) of the confidence region. An early proposal of the present author (Johns 1975) was to generate the ordering by means of a simple function of the observations which was asymptotically equivalent to the maximum likelihood confidence bound. This method guarantees asymptotic optimality when the numbers of component failures observed under testing is large. It was found, however, that the resulting bounds could be noticeably improved for small to moderate numbers of observed failures by more sophisticated methods. Another procedure investigated (Johns 1977) was a sequential method for generating the sample ordering starting at the origin (zero component failures observed) and selecting at each stage as the next sample

point the "adjacent" point producing the largest value for the lower bound on reliability. This method, while intuitively appealing, does not generally produce a "best" ordering as has been suggested by some investigators. In particular, it is improved upon by the method adopted in the present paper.

The non-existence of a unique optimal ordering leaves open the possibility of obtaining a confidence bound which is at least admissible by choosing the sample ordering to minimize the expected length of the confidence interval under some suitable prior distribution. Such a semi-Bayesian approach does not in any way impair the frequentistic interpretation of the confidence bounds obtained from the minimizing ordering. The implementation of such a minimization, while theoretically perfectly possible, turns out to be totally unfeasible computationally except for the earliest part of the ordering generated. Nevertheless, for a class of priors chosen to emulate certain properties of maximum likelihood, fragmentary orderings computed by this method provide a considerable justification for the two-stage "look-ahead" sequential method actually used to generate the tables which are a principal concern of this paper.

Suppose that the series system under consideration consists of  $k$  independent components and that the respective probabilities of component failure are  $p_i = 1 - q_i$ ,  $i = 1, 2, \dots, k$ . The system reliability  $R$  is given by

$$R = \prod_{i=1}^k q_i = \prod_{i=1}^k (1 - p_i) \quad . \quad (1.1)$$



If the observed numbers of failures for the  $k$  components are  $X_1, X_2, \dots, X_k$  based on independent tests with corresponding sample sizes  $n_1, n_2, \dots, n_k$ , we let  $\lambda_i = n_i p_i$ ,  $i = 1, 2, \dots, k$ , so that

$$R = \prod_{i=1}^k (1 - \lambda_i/n_i) \approx 1 - \sum_{i=1}^k \lambda_i/n_i . \quad (1.2)$$

The approximation on the right will be best when the  $p_i$ 's ( $= \lambda_i/n_i$ ) are all small which is just the case where  $R$  is close to one and the Poisson approximation for the distributions of the  $X_i$ 's is valid.

It will be convenient to express the problem in a canonical form by introducing some further notation. Let  $c = \sum_{i=1}^k 1/n_i$  and  $a_i = 1/cn_i$ ,  $i = 1, 2, \dots, k$ . Then letting  $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_k)$  and

$$\theta(\lambda) = \sum_{i=1}^k a_i \lambda_i , \quad (1.3)$$

we have

$$R \approx 1 - c \sum_{i=1}^k a_i \lambda_i = 1 - c\theta(\lambda) . \quad (1.4)$$

We shall assume henceforth that the components are indexed so that  $n_1 \geq n_2 \geq \dots \geq n_k$  which implies that  $a_1 \leq a_2 \leq \dots \leq a_k$ . The problem of finding a lower confidence bound for  $R$  is thus reduced to that of finding an upper confidence bound for  $\theta(\lambda)$ . The fact that  $\theta(\lambda)$  is a convex combination of the  $\lambda_i$ 's facilitates tabulation of the bounds by reducing the number of classification variables by one. In principle, confidence bounds for  $R$  could be constructed directly without introducing the approximation (1.2). Such an approach would,

however, eliminate the possibility of constructing useful tables of bounds, since separate entries would be required for every configuration of  $(n_1, n_2, \dots, n_k)$ .

The vector of observations is  $X = (X_1, X_2, \dots, X_k)$  so that the sample space on which a total ordering must be imposed consists of all vectors  $x = (x_1, x_2, \dots, x_k)$  where the  $x_i$ 's are non-negative integers. It seems reasonable to confine attention to orderings which are consistent with the natural partial ordering induced by dominance (see Section 2), and we shall do so. In Section 2 it is shown that the best upper confidence bound for  $\theta(\lambda)$  with confidence coefficient  $1 - \alpha$  which is monotone in a prescribed total ordering (designated by the relation  $\leq$ ) is given by

$$t(x) = \sup_{\lambda \in S_\alpha^*(x)} \theta(\lambda) , \quad (1.5)$$

where  $S_\alpha^*(x) = \{\lambda : P_\lambda\{X \leq x\} = \alpha\}$ . From (1.4) the lower confidence bound for system reliability is then given by

$$r(x) = 1 - ct(x) . \quad (1.6)$$



Because of the additive property of independent Poisson observations the effective number of components in the system may be reduced if some sample sizes are equal (or nearly equal) as follows: Suppose  $n_1 = n_2 = \dots = n_r = n$  for some  $r$ ,  $2 \leq r < k$ . Then  $a_1 = a_2 = \dots = a_r = a^*$  (say) and letting  $\lambda^* = \sum_{i=1}^r \lambda_i$  we have

$$\theta(\lambda) = a^* \lambda^* + \sum_{i=r+1}^k a_i \lambda_i. \quad (1.7)$$

Now  $X^* = \sum_{i=1}^r X_i$  has a Poisson distribution with parameter  $\lambda^*$  so that the right hand side of (1.7) has the correct form for the case of dimension  $k^* = k - r + 1$  except that the coefficients must each be divided by  $c_0 = a^* + a_{r+1} + \dots + a_k$  to preserve convexity. The confidence bound for the  $k^*$  dimensional case based on  $X^*, X_{r+1}, \dots, X_k$  and the normalized coefficients may then be multiplied by  $c_0$  to obtain the bound for the original  $\theta(\lambda)$  given by (1.7). Further reductions may be made in the same way if several groups of components have common sample sizes. If  $n_1, n_2, \dots, n_r$  are only approximately equal, their average may be used for  $n$  in the above calculations to obtain an approximate bound.

If all components are subjected to the same number of trials, we may take  $k$  equal to one and the problem reduces to the familiar one of finding an upper confidence bound for a single Poisson parameter.

The component failure data may be developed through independent testing of the components, or through testing of the complete system with the assignment of failures to the appropriate components.

Even in the latter case component sample sizes may differ if components are redesigned during the course of testing so that the trials and failures observed prior to redesign are not relevant to the reliability of the final version of the system.

It is worth noting that the same formal confidence bound problem arises from a somewhat different and more restrictive model involving continuous time sampling and exponentially distributed failure times. Thus, if we assume that the time to failure of the  $i$ -th component has the exponential probability density function  $\mu_i e^{-\mu_i t}$ ,  $\mu_i > 0$ ,  $t > 0$ , and if the fixed aggregate testing time for the  $i$ -th component is given by  $\tau_i$  and the total number of failures observed is  $X_i$ ,  $i=1,2,\dots,k$ , then the  $X_i$ 's which are sufficient statistics have independent Poisson distributions with corresponding parameters  $\lambda_i = \mu_i \tau_i$ . Such test data would be generated, for example, if a single unit of each component were placed on test and repaired whenever a failure occurred until the total test time for each component reached its corresponding limit,  $\tau_i$ . The system reliability for a single duty cycle (consisting of operation for a unit interval of time) is given by

$$R = \prod_{i=1}^k e^{-\mu_i \tau_i} = \exp \left\{ - \sum_{i=1}^k \mu_i \tau_i \right\} = \exp \left\{ - \sum_{i=1}^k \lambda_i \right\}, \quad (1.8)$$

and the confidence bound problem is essentially the same as the one previously introduced except that no approximations are required.

The general theory of confidence bounds based on sample orderings is discussed in Section 2. In Section 3 the case of systems having two components is considered in detail, and the rational for, and use of, the tables for this case are explained. Section 4 includes suggestions for constructing approximate confidence bounds for cases of systems with  $k \geq 3$  by finding approximately equivalent cases with  $k = 2$ . Use of the maximum likelihood ratio bounds for cases where the data are beyond the limits of the available tables is also discussed.

## 2. Bounds and Orderings: Generalities

The idea of using sample orderings to generate confidence bounds was first introduced by Buehler (1957) who discussed the validity of the proposed method in the context of a specific reliability problem. Bol'shev and Loginov (1969) discuss the construction of confidence bounds monotone in the sample orderings generated by certain functions of the observations. In the following, which is a revision and extension of Johns (1975), we develop the theory with emphasis on the sample orderings themselves rather than possible generators of the orderings.

To develop the general ideas relating exact confidence bounds to sample orderings it is convenient to introduce a fairly abstract statistical model. Let the sample space  $\mathcal{X}$  be endowed with a measurable total ordering relation " $\leq$ " and let  $X$  represent the random outcome of the experiment where the space of possible outcomes is  $\mathcal{X}$ . Suppose that the possible distributions of  $X$  are determined by the family of probability measures  $P_\lambda$ , indexed by  $\lambda$ , an element of the parameter space  $\Lambda$ . Our objective is to find a  $1 - \alpha$  level upper confidence bound for a specified real-valued function  $\theta(\lambda)$  defined on  $\Lambda$  where the range  $T$  of  $\theta(\lambda)$  is assumed to be closed and bounded below. The quantity  $\alpha \in (0,1)$  is regarded as fixed throughout. We make the following definitions and assumptions:

Definition D1. For each  $x \in \mathcal{X}$  let

$$S_\alpha(x) = \{\lambda : P_\lambda\{X \leq x\} > \alpha\} . \quad (2.1)$$

Definition D2. For each  $x \in \mathcal{X}$  let

$$t(x) = \begin{cases} \sup\{\theta(\lambda) : \lambda \in S_\alpha(x)\} , & \text{if } S_\alpha(x) \text{ is non-empty} , \\ \inf T, & \text{otherwise} . \end{cases} \quad (2.2)$$

Remark 1. By D2 if  $\theta(\lambda) > t(x)$ , then necessarily  $P_\lambda\{X \leq x\} \leq \alpha$ .

Assumption A1. For every subset  $C$  of  $\mathcal{X}$  having the property that if  $x \in C$  and  $y \leq x$  then  $y \in C$ , there exists an ordered sequence

$x_1 \leq x_2 \leq \dots$  of elements of  $C$  such that  $C = \bigcup_{n=1}^{\infty} \{x : x \leq x_n\}$ .

Assumption A2. For each  $x \in \mathcal{X}$ , if  $\theta(\lambda) = t(x)$ , then  $P_\lambda\{X \leq x\} \leq \alpha$ .

Remark 2. By D1, D2, and A2 if  $\theta(\lambda) = t(x)$ , then  $\lambda \notin S_\alpha(x)$ , i.e., the supremum in D2 is never attained.

We now establish the following propositions.

Proposition P1. The function  $t(x)$  is monotone in the ordering on  $\mathcal{X}$ .

Proof: If  $x, y \in \mathcal{X}$  and  $x \leq y$ , then  $S_\alpha(x) \subset S_\alpha(y)$  (D1) which in turn implies  $t(x) \leq t(y)$  (D2).  $\square$

Proposition P2. Under assumptions A1 and A2 the function  $t(x)$  is an upper confidence bound for  $\theta(\lambda)$  at level  $1 - \alpha$ . In particular,

$$P_\lambda\{\theta(\lambda) < t(X)\} \leq \alpha \quad \text{for all } \lambda \in \Lambda. \quad (2.3)$$

Proof: For arbitrary  $\lambda_0 \in \Lambda$ , let  $\theta_0 = \theta(\lambda_0)$  and  $C_0 = \{x: t(x) \leq \theta_0\}$ .

The result follows immediately for all  $\lambda_0$  for which  $C_0$  is empty.

Assume that  $C_0$  is non-empty. Then by P1 the set  $C_0$  possesses the property required in A1 for the existence of a sequence  $\{x_n\} \subset C_0$  such that  $x_n \leq x_{n+1}$  for all  $n$ , and  $C_0 = \bigcup_{n=1}^{\infty} \{x: x \leq x_n\}$ . This implies that, as  $n \rightarrow \infty$ ,

$$P_{\lambda_0}\{X \leq x_n\} \uparrow P_{\lambda_0}\{X \in C_0\}. \quad (2.4)$$

But by Remark 1 and A2, for all  $n$ ,  $P_{\lambda_0}\{X \leq x_n\} < \alpha$ . Hence

$P_{\lambda_0}\{X \in C_0\} \leq \alpha$  and the desired result follows.  $\square$

Proposition P3. Under assumptions A1 and A2, if  $\tilde{t}(x)$  is any T-valued confidence bound such that  $P_\lambda\{\theta(\lambda) < \tilde{t}(X)\} \geq 1 - \alpha$  for all  $\lambda \in \Lambda$ , then

$$(i) \quad \sup_{y \leq x} \tilde{t}(y) \geq t(x) \quad \text{for all } x \in \mathcal{X}, \quad \text{and}$$

(ii) if  $t(x)$  is monotone in the ordering on  $\mathcal{X}$ , then

$$\tilde{t}(x) \geq t(x) \quad \text{for all } x \in \mathcal{X}.$$

Proof: First we assume that  $\tilde{t}(x)$  is monotone and establish (ii).

Suppose there exists an  $x' \in \mathcal{X}$  such that  $\tilde{t}(x') < t(x')$ . Then  $S_\alpha(x')$  must be non-empty and by Remark 2 following A2, the sup defining  $t(x')$  is not attained. Hence there exists a  $\lambda' \in S_\alpha(x')$  such that  $\tilde{t}(x') < \theta(\lambda') < t(x')$ , and  $P_{\lambda'}\{X \leq x'\} > \alpha$ . Thus by the monotonicity of  $\tilde{t}(x)$ ,

$$P_\lambda\{\tilde{t}(X) \leq \theta(\lambda')\} \geq P_\lambda\{\tilde{t}(X) \leq \tilde{t}(x')\} = P_{\lambda'}\{X \leq x'\} > \alpha. \quad (2.5)$$

This contradicts the hypothesis that  $P_\lambda\{\theta(\lambda) < \tilde{t}(X)\} \geq 1 - \alpha$  for all  $\lambda$  and establishes (ii). To show (i) we let  $t^*(x) = \sup_{y \leq x} \tilde{t}(y)$  and observe that  $t^*(x)$  is monotone in the ordering on  $\mathcal{X}$  and  $t^*(x) \geq \tilde{t}(x)$  for all  $x \in \mathcal{X}$ . Hence if  $\tilde{t}(x)$  is a  $1 - \alpha$  confidence bound for  $\theta(\lambda)$ , so is  $t^*(x)$  and applying (ii) to  $t^*(x)$  yields (i).  $\square$ .

In order to specialize these results in the direction of applications we henceforth assume that the parameter  $\lambda$  and the

observation  $X$  are both of dimension  $k$ , i.e.,  $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_k)$  and  $X = (X_1, X_2, \dots, X_k)$  where the  $\lambda_i$ 's are real and the  $X_i$ 's are random variables. Without essential loss of generality we assume that  $\Lambda$  contains the positive orthant. Within this framework we make the following additional assumptions:

Assumption A3. The function  $\theta(\lambda)$  is continuous and strictly increasing in each of the  $\lambda_i$ 's.

Assumption A4. For any  $x \in \mathcal{X}$ ,  $P_\lambda\{X \leq x\}$  is continuous in each of the  $\lambda_i$ 's.

Proposition P4. Assumptions A3 and A4 imply that Assumption A2 is satisfied.

Proof: Suppose that for some  $x' \in \mathcal{X}$  there exists a  $\lambda' \in \Lambda$  such that  $\theta(\lambda') = t(x')$  and  $P_{\lambda'}\{X \leq x'\} > \alpha$ . Then by A3 and A4 we can find a  $\lambda'' \in \Lambda$  with  $\lambda_i'' \geq \lambda_i'$  for all  $i$  and  $\lambda_{i_0}'' > \lambda_{i_0}'$  for some  $i_0$  such that  $\theta(\lambda'') > t(x')$  and  $P_{\lambda''}\{X \leq x'\} > \alpha$ . This contradicts D2 and the result follows.  $\square$

Corollary C1. If (i) the observations  $X_1, X_2, \dots, X_k$  are independent Poisson random variables with parameters  $\lambda_1, \lambda_2, \dots, \lambda_k$  respectively, and (ii)  $\theta(\lambda) = a_1\lambda_1 + a_2\lambda_2 + \dots + a_k\lambda_k$  where the  $a_i$ 's are positive, then  $t(x)$  given by D2 is an upper confidence bound for  $\theta(\lambda)$  at level  $1 - \alpha$ .



Proof: A1 is satisfied for any ordering since  $\mathcal{X}$  is discrete. A3 is clearly satisfied for  $\theta(\lambda)$  of the form given by (ii), and A4 is satisfied for Poisson random variables. The desired result follows from P4 and P2.  $\square$

The actual computation of the bound  $t(x)$  given by D2 is greatly facilitated if  $P_\lambda\{X \leq x\}$  is monotone in the components of  $\lambda$ . The following proposition gives conditions guaranteeing this property:

Assumption A5. The components of  $X$  are independent and for  $i=1,2,\dots,k$  the distribution of each  $X_i$  depends only on the corresponding  $\lambda_i$  and is stochastically increasing in  $\lambda_i$ .

Definition D3. We denote by  $(\preceq^*)$  the natural partial ordering of  $\mathcal{X}$  generated by componentwise dominance. That is,  $x \preceq^* y$  if and only if  $x_i \leq y_i$  for  $i=1,2,\dots,k$ , with  $x \prec^* y$  if at least one of these inequalities is strict. An arbitrary total ordering  $(\preceq)$  on  $\mathcal{X}$  is consistent with  $(\preceq^*)$  if  $x \preceq^* y$  implies  $x \preceq y$ .

Proposition P5. If the ordering on  $\mathcal{X}$  is consistent with the natural partial ordering and Assumption A5 is satisfied, then for each  $x \in \mathcal{X}$ ,  $P_\lambda\{X \leq x\}$  is non-increasing in each component of  $\lambda$ .

Proof: For  $y \in \mathcal{X}$  we introduce the representation  $y = (y_1, y^{(2)})$  where  $y^{(2)} = (y_2, y_3, \dots, y_k)$ . For real  $z$ , fixed  $x \in \mathcal{X}$ , and all  $y \in \mathcal{X}$ , let  $I_{x,z,y^{(2)}}$  be the indicator function of the set  $\{y^{(2)} : (z, y^{(2)}) \leq x\}$ .

Then

$$P_{\lambda}\{X \leq x\} = E_{\lambda} I_x(X_1, X^{(2)}) \quad (2.6)$$

For any  $y \in \mathcal{X}$ , if  $z' \leq z''$ , then  $(z', y^{(2)}) \not\leq (z'', y^{(2)})$ , by the consistency hypothesis, and  $I_x(z', y^{(2)}) \geq I_x(z'', y^{(2)})$ . Hence letting  $G_x(z) = E_{\lambda}\{I_x(X_1, X^{(2)}) | X_1 = z\}$  we see that  $G_x(z)$  is non-increasing in  $z$ . Thus, since the distribution of  $X_1$  is stochastically increasing in  $\lambda_1$  (A5), we conclude that  $E_{\lambda} I_x(X_1, X^{(2)}) = E_{\lambda} G_x(X_1)$  is non-increasing in  $\lambda_1$ . The same argument applies to the other components of  $\lambda$  establishing the desired result.  $\square$

Suppose that  $\Lambda$  is the non-negative orthant of  $R^{(k)}$  and let  $\mathcal{S}$  be the simplex  $\mathcal{S} = \{\lambda : \sum_{i=1}^k \lambda_i = 1\}$ . If A4 and A5 are satisfied, then by P5 we observe that for any  $\lambda \in \mathcal{S}$  and real  $c$ ,  $P_{c\lambda}\{X \leq x\}$  is continuous and non-increasing in  $c$ . If the lower bound of  $P_{c\lambda}\{X \leq x\}$  as  $c \rightarrow \infty$  is less than  $\alpha$  for all  $x \in \mathcal{X}$  and all  $\lambda \in \mathcal{S}$ , then for each  $x \in \mathcal{X}$  and  $\lambda \in \mathcal{S}$  there exists a smallest number  $b = b(x, \lambda)$  such that  $P_{b(x, \lambda)\lambda}\{X \leq x\} = \alpha$ . The confidence bound  $t(x)$  defined by D2 is then given by

$$t(x) = \sup_{\lambda \in \mathcal{S}} \theta(b(x, \lambda)\lambda) \quad (2.7)$$

Now  $b(x, \lambda)$  is easily computed using root-finding techniques so that the computation of  $t(x)$  reduces to searching over  $\mathcal{S}$  for the maximum of  $\theta(b(x, \lambda)\lambda)$ . Many routines are available for implementing such searches. For the situation described in Corollary C1, the value of

b such that  $P_{b\lambda}\{X \leq x\} = \alpha$  is unique and (2.7) is a computationally feasible version of (1.5).

All of the above results apply mutatis mutandis to the construction of lower confidence bounds and hence confidence intervals. Applications to the reliability of coherent systems involving the binomial or other distributions are possible. In particular, the above discussion applies directly to the binomial case under the transformation  $\lambda_i = -\log(1-p_i)$ ,  $i = 1, 2, \dots, k$ ;  
 $\theta(\lambda) = \sum_{i=1}^k \lambda_i = -\log \prod_{i=1}^k (1-p_i)$ .

### 3. Systems With $k = 2$

As was noted in Section 1, if the system has effectively only one component (e.g., when all sample sizes are equal), then the problem reduces to the well-known case of finding an upper confidence bound for a single Poisson parameter. Then in the notation of Section 1,  $\theta(\lambda) = \lambda$  and if  $t(x)$  is the confidence bound for  $\lambda$ , the lower confidence bound (1.6) for reliability  $R$  becomes

$$r(x) = 1 - t(x)/n, \quad (3.1)$$

where  $n$  is the (common) sample size.

The two component case ( $k = 2$ ) presents all of the difficulties of the general case. The principal problem is to generate an ordering of the sample points  $x = (x_1, x_2)$  which will lead to a "good" confidence bound  $t(x)$  computed using (1.5) or (2.7). Several different methods have been considered and implemented to varying extents

in the course of this investigation. These methods may be described briefly as follows:

- (i) The  $x$ 's are ordered according to the values of the function  $\tilde{t}(x) = a_1x_1 + a_2x_2 + z_\alpha \sqrt{a_1^2x_1^2 + a_2^2x_2^2}$ , where  $z_\alpha$  is the upper  $\alpha$ -th quantile of the standard normal distribution.
- (ii) The  $x$ 's are ordered according to the values of the approximate confidence bound obtained from the maximum likelihood ratio statistic (see Section 4).
- (iii) The ordering is generated sequentially by considering at each stage the group of points which are not yet ordered but could be adjoined without violating the natural partial ordering (see D3 of Section 2). The next point in the ordering is then chosen to be the "best" member of the candidate group, i.e., the point producing the smallest value of  $t(x)$  given by (1.5).
- (iv) The ordering is chosen so as to minimize  $E_G\{t(X)\}$  for some suitable prior distribution  $G$  over the values of  $\lambda$ .
- (v) The ordering is generated sequentially in the manner of (iii) above except that at each stage the candidate points for the next two steps are considered as pairs and the next point selected is the first step component which, together with the best available point for the second step, produces the smallest sum for the two values of  $t(x)$ . Note that the point that appears to be "best" two steps ahead may not actually be chosen when that stage is reached.

It is clear that none of these methods is special to the case  $k = 2$ . Method (i), based on the function  $\tilde{t}(x)$ , which is really a maximum likelihood estimate of an asymptotically valid confidence bound, was used to generate tables of bounds for the case  $k = 2$  in Johns (1975). Method (ii) does not improve substantially on Method (i) for moderate values of the  $X_i$ 's. Methods (i) and (ii) are asymptotically equivalent when at least one  $X_i$  becomes large (see Johns 1975) and indeed standard maximum likelihood results guarantee that both are asymptotically optimal. Method (iii) discussed in Johns (1977) was found to be a substantial improvement on (i) in the strong sense that when the Method (iii) ordering is used the values of  $t(x)$  are often smaller and only rarely slightly larger than the values for corresponding  $x$ 's produced by Method (i).

The semi-Bayesian approach of Method (iv), which minimizes the expected length of the confidence interval, is the only one of the five that is directly motivated by optimality considerations. The bound resulting from any reasonable prior must at least be admissible. In pursuing this approach it was decided in the spirit of objectivity and in the hope of rapid convergence to asymptotic optimality to choose a prior distribution leading to an unconditional probability mass function for  $x_1$  and  $x_2$  constant for constant values of the maximum likelihood estimator  $a_1x_1 + a_2x_2$  for  $\theta(\lambda)$ . In particular, the prior density for  $\lambda_1$  and  $\lambda_2$  was taken to be

$$g(\lambda_1, \lambda_2) = b_1 b_2 e^{-b_1 \lambda_1 - b_2 \lambda_2}, \lambda_1, \lambda_2 > 0, \quad (3.2)$$

where  $b_1 = (1 - e^{-\beta a_1})$ ,  $b_2 = (1 - e^{-\beta a_2})$ ,  $\beta > 0$ . This produces the unconditional probability mass function

$$p(x_1, x_2) = b_1 b_2 e^{-\beta(a_1 x_1 + a_2 x_2)}, \quad x_1, x_2 = 0, 1, \dots, \quad (3.3)$$

In the limiting case, as  $\beta \rightarrow 0$ ,  $p(x_1, x_2)$  becomes essentially uniform over any finite set of points  $(x_1, x_2)$ .

The actual minimization of  $E_G\{t(X)\}$  may, in principle, be accomplished by finding the ordering which minimizes the contribution to  $E_G$  among all orderings of length  $N$  where  $N$  may be arbitrarily large. This may be done systematically by starting at the origin  $(0, 0)$  and constructing a tree whose nodes at each stage are characterized by a candidate point newly adjoined to the ordering and the corresponding value of  $\sum p(x)t(x)$ , where the sum is taken over all  $x$ 's occurring in the path leading to the node, including the one just adjoined. At the  $N$ -th stage the node having the smallest accumulated sum identifies the optimal ordering of length  $N$ . This process may be facilitated by eliminating duplicate nodes and discontinuing branches when a node is reached whose value exceeds that known to be attainable in  $N$  stages. Nevertheless, because of the rapid increase in the number of nodes considered per stage, only the first forty or so points in the optimal orderings could be determined even using a very large computer facility.

In order to obtain examples of admissible orderings with which to compare the results of other methods, this computation was performed for two cases using an IBM 370/168. For both cases the

values  $\alpha = .10$  and  $a_1 = .30$  were used. For the first case the probabilities given in (3.3) with  $\beta = 1$  were used and the first 41 points of the optimal ordering were obtained. The forty-first stage of the computation produced 4557 nodes. For the second case the limiting situation as  $\beta \rightarrow 0$  where the  $p(x)$ 's are all equal was used and the first 43 points of the optimal ordering were obtained. The number of nodes produced at the forty-third stage was 6478.

A comparison of these results with the corresponding results obtained using Methods (i), (iii), and (v) is indicated in Figure 1. The horizontal axis indexes the first 50 points in the ordering produced by Method (v), the two-step prospective sequential procedure. The values of  $t(x)$  for these indexed points for the five methods are indicated by the plotted symbols. Values of  $t(x)$  for methods other than (v) are shown only when they differ from those produced by that method. Based on this evidence it appears that Method (iv) and Method (v) differ very little and that both are better than the other methods. In fact, Method (iv) for the uniform case ( $\beta = 0$ ) differs only trivially from Method (v). Since the use of Method (iv) for the construction of tables is now and probably always will be impractical, we are led to the choice for this purpose of the more tractable and virtually equivalent Method (v). Prospective sequential methods looking ahead more than two steps might be feasible, although the complexity of the computations increases rapidly with the number of steps. However, such procedures would be expected to produce only minute improvement over the two-step method.



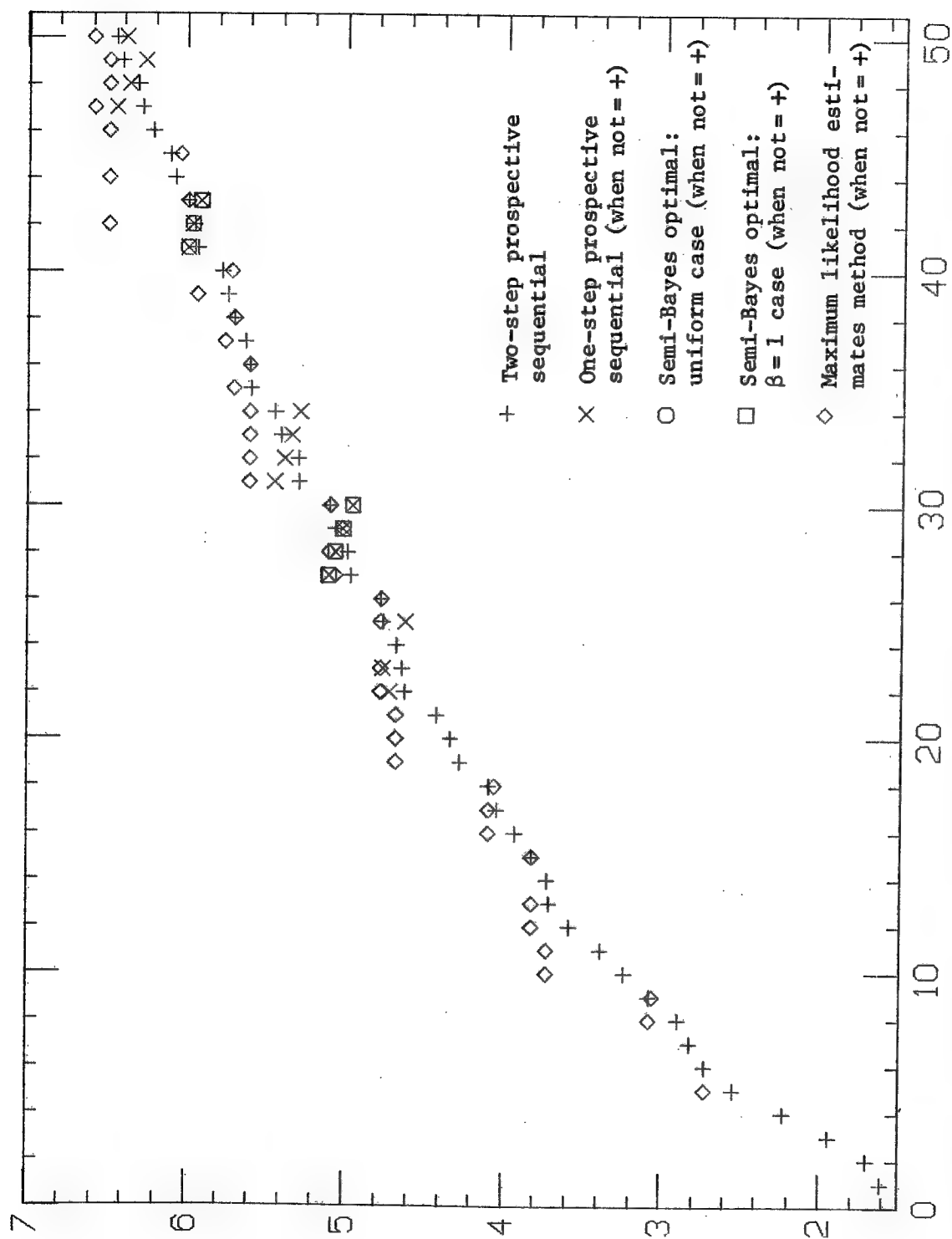


Figure 1. Comparison of confidence bounds for five ordering methods:  $\alpha = .10$ ,  $a_1 = .30$

Table 1 gives values of the upper confidence bound  $t(x)$  computed using (2.7) with the sample orderings generated by the two-step prospective sequential Method (v). The values are given for the first 100 points in each ordering for  $\alpha = .01, .05, .10$ , for  $a_1 = .05(.05).45$ . It is assumed that the components of the system are indexed so that  $a_1 < a_2$  which implies  $a_1 < .50$ . For convenience the values of  $(x_1, x_2)$  are listed systematically rather than in the order generated by the two-step procedure. This table provides a basis for computing accurate confidence bounds for the case  $k = 2$  using only simple interpolation. If values of  $a_1$  greater than .45 but (necessarily) less than .50 are required, the bound for  $a_1 = .5$  (corresponding to  $n_1 = n_2$ ) may be used for interpolation. This bound is obtained by simply multiplying the ordinary upper confidence bound for a single Poisson parameter based on  $x = x_1 + x_2$  failures by .50 (see, e.g., Pearson and Hartley 1958 for tables). The use of Table 1 is illustrated by the following two examples:

Example 1. Suppose that the two components of a series system are tested independently using sample sizes  $n_1 = 300$  and  $n_2 = 100$  respectively with the corresponding observed numbers of failures  $X_1 = 3$  and  $X_2 = 4$ . Then  $c = (1/300 + 1/100) = 4/300$  and  $a_1 = 1/cn_1 = .25 = 1 - a_2$ . If we wish to find a 95 percent confidence interval, we take  $\alpha = .05$ , and from Table 1 we find the confidence bound  $t(x)$  for  $\theta(\lambda)$  to be 7.333. Hence by (1.6) the 95 percent lower confidence bound for system reliability  $R$  is  $1 - (4/300)(7.333) = .902$ .

Table 1. The Confidence Bound  $t(x)$  for  $k = 2$  for the First 100 Points Generated by the Two-Stage Optimal Ordering Method for Each  $a_1$  and  $\alpha$ .

$a_1 = 0.05$				$a_1 = 0.05$				$a_1 = 0.05$				$a_1 = 0.05$				$a_1 = 0.10$			
$x_1$	$x_2$	$t(x_1, x_2)$	$t(x_1, x_2)$	$x_1$	$x_2$	$t(x_1, x_2)$	$t(x_1, x_2)$	$x_1$	$x_2$	$t(x_1, x_2)$	$t(x_1, x_2)$	$x_1$	$x_2$	$t(x_1, x_2)$	$t(x_1, x_2)$	$x_1$	$x_2$	$t(x_1, x_2)$	$t(x_1, x_2)$
0	0	4.375	5.262	0	0	2.846	3.733	0	0	2.188	3.075	0	0	2.188	3.075	0	0	2.188	3.075
0	1	6.306	7.195	0	1	4.507	5.396	0	1	3.695	4.585	0	1	3.695	4.585	0	1	3.695	4.585
1	0	4.376	5.306	1	0	2.847	3.777	1	0	2.189	3.119	1	0	2.189	3.119	1	0	2.189	3.119
1	1	6.308	7.239	1	1	4.508	5.440	1	1	3.697	4.629	1	1	3.697	4.629	1	1	3.697	4.629
2	0	4.387	5.351	2	0	2.858	3.822	2	0	2.200	3.163	2	0	2.200	3.163	2	0	2.200	3.163
2	1	6.319	7.284	2	1	4.519	5.485	2	1	3.708	4.674	2	1	3.708	4.674	2	1	3.708	4.674
3	0	4.407	5.395	3	0	2.878	3.866	3	0	2.220	3.208	3	0	2.220	3.208	3	0	2.220	3.208
3	1	6.327	7.329	3	1	4.539	5.529	3	1	3.727	4.718	3	1	3.727	4.718	3	1	3.727	4.718
4	0	4.432	5.440	4	0	2.903	3.911	4	0	2.245	3.253	4	0	2.245	3.253	4	0	2.245	3.253
4	1	6.364	7.485	4	1	4.564	5.574	4	1	3.753	4.763	4	1	3.753	4.763	4	1	3.753	4.763
5	0	4.461	5.530	5	0	2.932	3.956	5	0	2.274	3.298	5	0	2.274	3.298	5	0	2.274	3.298
5	1	6.393	7.576	5	1	4.593	5.619	5	1	3.781	4.809	5	1	3.781	4.809	5	1	3.781	4.809
6	0	4.493	5.621	6	0	2.964	4.001	6	0	2.305	3.343	6	0	2.305	3.343	6	0	2.305	3.343
6	1	6.424	7.667	6	1	4.624	5.665	6	1	3.813	4.854	6	1	3.813	4.854	6	1	3.813	4.854
7	0	4.526	5.712	7	0	2.997	4.047	7	0	2.339	3.388	7	0	2.339	3.388	7	0	2.339	3.388
7	1	6.458	7.758	7	1	4.658	5.692	7	1	3.847	4.899	7	1	3.847	4.899	7	1	3.847	4.899
8	0	4.561	5.804	8	0	3.032	4.138	8	0	2.374	3.434	8	0	2.374	3.434	8	0	2.374	3.434
8	1	6.493	7.804	8	1	4.693	5.730	8	1	3.882	4.945	8	1	3.882	4.945	8	1	3.882	4.945
9	0	4.598	5.896	9	0	3.069	4.229	9	0	2.410	3.479	9	0	2.410	3.479	9	0	2.410	3.479
9	1	6.529	7.942	9	1	4.730	5.775	9	1	3.918	5.001	9	1	3.918	5.001	9	1	3.918	5.001
10	0	4.635	5.989	10	0	3.106	4.321	10	0	2.447	3.525	10	0	2.447	3.525	10	0	2.447	3.525
10	1	6.567	8.035	10	1	4.767	5.816	10	1	3.956	5.051	10	1	3.956	5.051	10	1	3.956	5.051
11	0	4.673	6.081	11	0	3.144	4.413	11	0	2.486	3.571	11	0	2.486	3.571	11	0	2.486	3.571
11	1	6.605	8.128	11	1	4.805	5.862	11	1	3.994	5.096	11	1	3.994	5.096	11	1	3.994	5.096
12	0	4.712	6.174	12	0	3.183	4.506	12	0	2.525	3.622	12	0	2.525	3.622	12	0	2.525	3.622
12	1	6.644	8.221	12	1	4.845	5.907	12	1	4.033	5.147	12	1	4.033	5.147	12	1	4.033	5.147
13	0	4.752	6.268	13	0	3.223	4.599	13	0	2.565	3.667	13	0	2.565	3.667	13	0	2.565	3.667
13	1	6.684	8.315	13	1	4.884	5.952	13	1	4.073	5.191	13	1	4.073	5.191	13	1	4.073	5.191
14	0	4.792	6.362	14	0	3.264	4.692	14	0	2.605	3.716	14	0	2.605	3.716	14	0	2.605	3.716
14	1	6.724	8.409	14	1	4.925	6.043	14	1	4.114	5.239	14	1	4.114	5.239	14	1	4.114	5.239
15	0	4.833	6.456	15	0	3.304	4.739	15	0	2.646	3.760	15	0	2.646	3.760	15	0	2.646	3.760
15	1	6.765	8.453	15	1	4.966	6.095	15	1	4.154	5.281	15	1	4.154	5.281	15	1	4.154	5.281
16	0	4.875	6.550	16	0	3.346	4.833	16	0	2.687	3.801	16	0	2.687	3.801	16	0	2.687	3.801
16	1	6.807	8.507	16	1	5.007	6.141	16	1	4.196	5.323	16	1	4.196	5.323	16	1	4.196	5.323
17	0	4.916	6.644	17	0	3.388	4.927	17	0	2.729	3.847	17	0	2.729	3.847	17	0	2.729	3.847
17	1	6.849	8.559	17	1	5.049	6.183	17	1	4.238	5.365	17	1	4.238	5.365	17	1	4.238	5.365
18	0	4.959	6.739	18	0	3.430	5.068	18	0	2.771	3.894	18	0	2.771	3.894	18	0	2.771	3.894
18	1	6.891	8.614	18	1	5.091	6.229	18	1	4.280	5.401	18	1	4.280	5.401	18	1	4.280	5.401
19	0	5.001	6.834	19	0	3.472	5.163	19	0	2.814	3.934	19	0	2.814	3.934	19	0	2.814	3.934
19	1	6.933	8.681	19	1	5.134	6.271	19	1	4.323	5.441	19	1	4.323	5.441	19	1	4.323	5.441
20	0	5.044	6.929	20	0	3.515	5.257	20	0	2.856	3.979	20	0	2.856	3.979	20	0	2.856	3.979
20	1	6.976	8.727	20	1	5.177	6.315	20	1	4.366	5.486	20	1	4.366	5.486	20	1	4.366	5.486
21	0	5.087	7.024	21	0	3.558	5.305	21	0	2.900	4.021	21	0	2.900	4.021	21	0	2.900	4.021
21	1	7.019	8.772	21	1	5.220	6.353	21	1	4.409	5.523	21	1	4.409	5.523	21	1	4.409	5.523
22	0	5.130	7.120	22	0	3.601	5.400	22	0	2.943	4.067	22	0	2.943	4.067	22	0	2.943	4.067
22	1	7.063	8.816	22	1	5.264	6.395	22	1	4.453	5.569	22	1	4.453	5.569	22	1	4.453	5.569
23	0	5.174	7.215	23	0	3.645	5.543	23	0	2.987	4.114	23	0	2.987	4.114	23	0	2.987	4.114
23	1	7.107	8.863	23	1	5.307	6.439	23	1	4.496	5.614	23	1	4.496	5.614	23	1	4.496	5.614
24	0	5.218	7.311	24	0	3.689	5.639	24	0	3.031	4.161	24	0	3.031	4.161	24	0	3.031	4.161
24	1	7.151	8.909	24	1	5.351	6.486	24	1	4.540	5.666	24	1	4.540	5.666	24	1	4.540	5.666

Table 1. (Continued)

a1 = 0.1      alpha = 0.01				a1 = 0.1      alpha = 0.05				a1 = 0.1      alpha = 0.10			
x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)
0	0	4.145	17	0	5.384	0	0	2.696	16	1	5.426
0	1	5.975	17	1	7.221	0	1	4.269	16	2	6.827
0	2	7.565	18	0	5.477	0	2	5.666	17	0	3.936
1	0	4.151	18	1	7.314	0	3	6.978	17	1	5.519
1	1	5.981	19	0	5.569	1	0	2.702	17	2	6.920
1	2	7.571	19	1	7.407	1	1	4.275	18	0	4.028
2	0	4.184	20	0	5.662	1	2	5.672	18	1	5.612
2	1	6.014	20	1	7.501	2	0	2.735	19	0	4.121
2	2	7.605	21	0	5.756	2	1	4.309	19	1	5.706
3	0	4.235	21	1	7.596	2	2	5.706	20	0	4.214
3	1	6.065	22	0	5.850	3	0	2.787	20	1	5.800
3	2	7.656	22	1	7.691	3	1	4.360	21	0	4.307
4	0	4.297	23	0	5.945	3	2	5.757	21	1	5.895
4	1	6.127	23	1	7.786	4	0	2.849	22	0	4.402
4	2	7.718	24	0	6.040	4	1	4.422	22	1	5.991
5	0	4.366	24	1	7.882	4	2	5.819	23	0	4.496
5	1	6.196	25	0	6.135	5	0	2.917	23	1	6.087
5	2	7.786	25	1	7.978	5	1	4.491	24	0	4.591
6	0	4.439	26	0	6.230	5	2	5.889	24	1	6.183
6	1	6.270	26	1	8.075	6	0	2.991	25	0	4.687
6	2	7.861	27	0	6.326	6	1	4.565	25	1	6.280
7	0	4.516	27	1	8.172	6	2	5.963	26	0	4.782
7	1	6.348	28	0	6.422	7	0	3.068	26	1	6.380
7	2	7.939	28	1	8.270	7	1	4.643	27	0	4.878
8	0	4.596	29	0	6.519	7	2	6.040	27	1	6.478
8	1	6.428	29	1	8.369	8	0	3.148	28	0	4.975
8	2	8.020	30	0	6.616	8	1	4.723	28	1	6.577
9	0	4.679	30	1	8.467	8	2	6.121	29	0	5.073
9	1	6.510	31	0	6.713	9	0	3.230	29	1	6.676
9	2	8.102	31	1	8.565	9	1	4.806	30	0	5.170
10	0	4.763	32	0	6.810	9	2	6.204	30	1	6.776
10	1	6.595	32	1	8.665	10	0	3.314	31	0	5.268
10	2	8.187	33	0	6.908	10	1	4.891	31	1	6.878
11	0	4.848	34	0	7.006	10	2	6.289	32	0	5.366
11	1	6.681	35	0	7.104	11	0	3.400	32	1	5.464
11	2	8.273	36	0	7.202	11	1	4.977	33	0	5.563
12	0	4.935	37	0	7.309	11	2	6.376	33	1	6.661
12	1	6.768	38	0	7.399	12	0	3.487	34	0	5.760
12	2	8.361	39	0	7.498	12	1	5.065	34	1	6.760
13	0	5.023	40	0	7.600	12	2	6.464	35	0	5.859
13	1	6.857	41	0	7.700	13	0	3.575	35	1	6.859
13	2	8.450	42	0	7.799	13	1	5.154	36	0	6.058
14	0	5.112	43	0	7.899	13	2	6.553	37	0	6.158
14	1	6.947	44	0	8.000	14	0	3.664	38	0	6.258
14	2	8.540	45	0	8.100	14	1	5.244	39	0	6.359
15	0	5.202	46	0	8.200	14	2	6.644	40	0	6.459
15	1	7.037	47	0	8.301	15	0	3.754	41	0	6.559
15	2	8.631	48	0	8.402	15	1	5.334	42	0	6.660
16	0	5.293	49	0	8.503	15	2	6.735	43	0	6.761
16	1	7.129	50	0	8.604	16	0	3.844	44	0	6.862
									45	0	6.963

Table 1. (Continued)

a1 = 0.15				alpha = 0.01				a1 = 0.15				alpha = 0.05				a1 = 0.15				alpha = 0.10			
x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)
0	0	3.914	7.143	13	1	7.143	2.546	0	0	2.546	3.883	12	0	3.883	0	0	0	1.957	11	2	5.755		
0	0	5.643	8.659	13	2	8.659	4.032	0	1	4.032	5.403	12	1	5.403	0	1	3.306	11	3	6.921			
0	0	7.145	5.538	14	0	5.538	5.351	0	2	5.351	6.728	12	2	6.728	0	2	4.524	12	0	3.293			
0	0	8.538	7.291	14	1	7.291	6.591	0	3	6.591	4.026	13	0	4.026	0	3	5.679	12	1	4.679			
1	0	3.929	8.809	14	2	8.809	7.780	0	4	7.780	5.560	13	1	5.560	0	4	6.795	12	2	5.905			
1	1	5.658	5.684	15	0	5.684	2.561	1	0	2.561	6.881	13	2	6.881	1	0	1.972	13	0	3.438			
1	1	7.160	7.443	15	1	7.443	4.047	1	1	4.047	4.171	14	0	4.171	1	1	3.321	13	1	4.836			
1	3	8.553	8.964	15	2	8.964	5.367	1	2	5.367	5.717	14	1	5.717	1	2	4.530	13	2	6.055			
2	0	3.994	5.831	16	0	5.831	6.606	1	3	6.606	7.034	14	2	7.034	1	3	5.694	14	0	4.993			
2	1	5.723	7.594	16	1	7.594	7.796	1	4	7.796	4.319	15	0	4.319	1	4	6.810	14	1	6.206			
2	2	7.225	9.117	16	2	9.117	2.626	2	0	2.626	5.874	15	1	5.874	2	0	2.037	14	2	6.206			
2	3	8.619	5.979	17	0	5.979	4.113	2	1	4.113	7.187	15	2	7.187	2	1	3.387	15	0	3.735			
3	0	4.087	7.747	17	1	7.747	5.432	2	2	5.432	4.468	16	0	4.468	2	2	4.605	15	1	5.150			
3	1	5.816	9.272	17	2	9.272	6.671	2	3	6.671	6.032	16	1	6.032	2	3	5.759	15	2	6.368			
3	2	7.319	6.128	18	0	6.128	2.719	3	0	2.719	7.341	16	2	7.341	2	4	6.875	16	0	3.884			
3	3	8.712	7.901	18	1	7.901	4.206	3	1	4.206	6.190	17	0	6.190	3	1	3.480	16	2	6.522			
4	0	4.194	9.427	18	2	9.427	5.525	3	2	5.525	7.496	17	1	7.496	3	2	4.698	17	0	4.035			
4	1	5.924	6.278	19	0	6.278	6.765	3	3	6.765	4.768	17	2	4.768	3	3	5.854	17	1	5.464			
4	2	7.427	8.056	19	1	8.056	2.826	4	0	2.826	6.348	18	0	6.348	4	0	2.237	18	0	4.186			
4	3	8.821	9.583	19	2	9.583	4.314	4	1	4.314	7.651	18	1	7.651	4	1	3.589	18	1	5.623			
5	0	4.311	6.429	20	0	6.429	5.635	4	2	5.635	4.919	18	2	4.919	4	2	4.808	18	2	6.830			
5	1	6.042	8.212	20	1	8.212	6.896	4	3	6.896	6.506	19	0	6.506	4	3	5.964	19	0	4.339			
5	2	7.546	9.588	21	0	9.588	2.943	5	0	2.943	5.072	19	1	5.072	5	0	2.354	19	1	5.780			
5	3	8.941	8.381	21	1	8.381	4.433	5	1	4.433	6.665	20	0	6.665	5	1	3.708	19	2	6.984			
6	0	4.435	6.741	22	0	6.741	5.754	5	2	5.754	5.225	20	1	5.225	5	2	4.928	20	0	4.491			
6	1	6.167	8.538	22	1	8.538	6.995	5	3	6.995	6.824	21	0	6.824	5	3	6.085	20	1	5.938			
6	2	7.672	9.896	23	0	9.896	3.067	6	0	3.067	5.378	21	1	5.378	6	0	2.478	21	0	4.645			
6	3	9.067	8.696	23	1	8.696	4.559	6	1	4.559	6.982	22	0	6.982	6	1	3.834	21	1	6.096			
7	0	4.564	7.050	24	0	7.050	5.881	6	2	5.881	7.141	22	1	7.141	6	2	5.056	22	0	4.799			
7	1	6.297	8.855	24	1	8.855	7.123	6	3	7.123	6.154	23	0	6.154	6	3	6.216	22	1	6.254			
7	2	7.803	9.014	25	0	9.014	3.196	7	0	3.196	5.687	23	1	5.687	7	0	2.606	23	0	4.954			
7	3	9.199	7.362	25	1	7.362	4.690	7	1	4.690	7.300	24	0	7.300	7	1	3.966	23	1	6.411			
8	0	4.696	8.173	26	0	8.173	6.013	7	2	6.013	5.843	24	1	5.843	7	2	5.189	24	0	5.109			
8	1	6.435	9.173	26	1	9.173	7.256	7	3	7.256	7.459	25	0	7.459	7	3	6.347	24	1	6.569			
8	2	7.939	7.519	27	0	7.519	3.328	8	0	3.328	5.998	25	1	5.998	8	0	2.739	25	0	5.264			
8	3	9.336	9.333	27	1	9.333	4.825	8	1	4.825	7.617	26	0	7.617	8	1	4.102	25	1	6.727			
9	0	4.831	7.675	28	0	7.675	6.150	8	2	6.150	6.154	26	1	6.154	8	2	5.327	26	0	5.419			
9	1	6.569	9.492	28	1	9.492	7.394	8	3	7.394	7.776	27	0	7.776	8	3	6.485	26	1	6.885			
9	2	8.078	7.833	29	0	7.833	3.463	9	0	3.463	6.310	27	1	6.310	9	0	2.874	27	0	5.575			
9	3	9.476	7.991	30	0	7.991	4.964	9	1	4.964	6.467	28	0	6.467	9	1	4.241	28	0	5.731			
10	0	4.969	8.148	31	0	8.148	6.290	9	2	6.290	7.536	29	0	7.536	9	2	5.469	29	0	5.887			
10	1	6.709	9.307	32	0	9.307	7.536	9	3	7.536	6.624	30	0	6.624	9	3	6.012	30	0	6.044			
10	2	8.223	8.465	33	0	8.465	3.601	10	0	3.601	6.781	31	0	6.781	10	0	3.012	31	0	6.201			
11	0	5.109	8.624	34	0	8.624	5.105	10	1	5.105	7.096	32	0	7.096	10	1	4.384	32	0	6.357			
11	1	6.852	8.783	35	0	8.783	6.433	10	2	6.433	7.253	33	0	7.253	10	2	5.610	33	0	6.514			
11	2	8.364	8.942	36	0	8.942	7.681	10	3	7.681	7.411	34	0	7.411	10	3	6.772	34	0	6.671			
12	0	5.251	9.101	37	0	9.101	3.741	11	0	3.741	7.569	35	0	7.569	11	0	4.529	35	0	6.828			
12	1	6.997	9.260	38	0	9.260	5.249	11	1	5.249	7.727	36	0	7.727	11	1	4.529	36	0	6.986			
12	2	8.510	9.420	39	0	9.420	7.829	11	2	7.829		37	0		11	2							
13	0	5.394	9.580	40	0	9.580		11	3			37	0		11	3							

Table 1. (Continued)

a1 = 0.2    alpha = 0.01				a1 = 0.2    alpha = 0.05				a1 = 0.2    alpha = 0.10			
x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)
0	0	3.684	10	2	8.377	0	0	2.397	9	3	7.664
0	1	5.311	10	3	9.716	0	1	3.795	10	0	3.982
0	2	6.725	11	0	5.469	0	2	5.037	10	1	5.440
0	3	8.036	11	1	7.153	0	3	6.203	10	2	6.697
0	4	9.284	11	2	8.590	0	4	7.323	10	3	7.873
1	0	3.714	11	3	9.938	0	5	8.410	11	0	4.187
1	1	5.341	12	0	5.676	1	0	2.427	11	1	5.652
1	2	6.755	12	1	7.381	1	1	3.825	11	2	6.908
1	3	8.067	12	2	8.805	1	2	5.067	11	3	8.084
1	4	9.314	12	3	10.155	1	3	6.233	12	0	4.395
2	0	3.821	13	0	5.885	1	4	7.353	12	1	5.665
2	1	5.449	13	1	7.598	1	5	8.441	12	2	7.120
2	2	6.864	13	2	9.020	2	0	2.534	12	3	8.295
2	3	8.176	14	0	6.096	2	1	3.934	13	0	4.605
2	4	9.424	14	1	7.815	2	2	5.176	13	1	6.158
3	0	3.965	14	2	9.236	2	3	6.343	13	2	7.332
3	1	5.595	15	0	6.308	2	4	7.464	13	3	8.506
3	2	7.011	15	1	8.034	2	5	8.552	14	0	4.816
3	3	8.324	15	2	9.452	3	0	2.677	14	1	6.320
3	4	9.573	16	0	6.522	3	1	4.081	14	2	7.544
4	0	4.128	16	1	8.252	3	2	5.325	15	0	5.072
4	1	5.761	16	2	9.669	3	3	6.493	15	1	6.536
4	2	7.179	17	0	6.776	3	4	7.614	15	2	7.757
4	3	8.494	17	1	8.471	4	0	2.840	16	0	5.288
4	4	9.744	17	2	9.845	4	1	4.248	16	1	6.752
5	0	4.302	18	0	6.996	4	2	5.496	16	2	7.970
5	1	5.940	18	1	8.691	4	3	6.664	17	0	5.506
5	2	7.361	18	2	10.060	4	4	7.787	17	1	6.967
5	3	8.678	19	0	7.216	5	0	3.015	17	2	8.183
5	4	9.926	19	1	8.910	5	1	4.430	18	0	5.723
6	0	4.485	19	2	10.276	5	2	5.681	18	1	7.183
6	1	6.129	20	0	7.436	5	3	6.850	18	2	8.397
6	2	7.552	20	1	9.129	5	4	7.975	19	0	5.941
6	3	8.872	21	0	7.657	6	0	3.198	19	1	7.399
6	4	10.118	21	1	9.349	6	1	4.640	20	0	6.104
7	0	4.674	22	0	7.877	6	2	5.890	20	1	7.614
7	1	6.339	22	1	9.569	6	3	7.044	21	0	6.376
7	2	7.750	23	0	8.098	6	4	8.172	21	1	7.830
7	3	9.075	23	1	9.886	7	0	3.386	22	0	6.594
7	4	10.316	24	0	8.319	7	1	4.855	22	1	8.046
8	0	4.867	24	1	10.103	7	2	6.066	23	0	6.812
8	1	6.557	25	0	8.540	7	3	7.244	23	1	8.262
8	2	7.954	26	0	8.761	7	4	8.375	24	0	7.029
8	3	9.285	27	0	8.982	8	0	3.579	24	1	8.477
9	0	5.064	28	0	9.203	8	1	5.019	25	0	7.247
9	1	6.729	29	0	9.425	8	2	6.269	26	0	7.465
9	2	8.161	30	0	9.646	8	3	7.449	27	0	7.683
9	3	9.500	31	0	9.802	9	0	3.776	28	0	7.901
10	0	5.264	32	0	10.023	9	1	5.230	29	0	8.119
10	1	6.940	33	0	10.244	9	2	6.474	30	0	8.337

Table 1. (Continued)

a1 = 0.25					alpha = 0.01					a1 = 0.25					alpha = 0.05					a1 = 0.25					alpha = 0.10				
x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)			
0	0	3.454	8	4	10.491	0	0	2.247	8	1	5.307	0	0	1.727	8	0	3.441	0	0	3.441	8	0	3.441	0	0	3.441			
0	1	4.979	9	0	5.406	0	1	3.558	8	2	6.432	0	1	2.917	8	1	4.715	0	1	4.715	8	1	4.715	0	1	4.715			
0	2	6.304	9	1	7.041	0	2	4.722	8	3	7.527	0	2	3.992	8	2	5.756	0	2	5.756	8	2	5.756	0	2	5.756			
0	3	7.534	9	2	8.345	0	3	5.815	8	4	8.680	0	3	5.011	8	3	6.827	0	3	6.827	8	3	6.827	0	3	6.827			
0	4	8.704	9	3	9.581	0	4	6.865	9	0	4.210	0	4	5.995	8	4	7.741	0	4	7.741	8	4	7.741	0	4	7.741			
0	5	9.831	9	4	10.815	0	5	7.885	9	1	5.686	0	5	6.956	9	0	3.716	0	5	3.716	9	0	3.716	0	5	3.716			
1	0	3.508	10	0	5.718	0	6	8.882	9	2	6.809	0	6	7.899	9	1	4.986	0	6	4.986	9	1	4.986	0	6	4.986			
1	1	5.033	10	1	7.325	1	0	2.301	9	3	7.907	1	0	1.781	9	2	6.022	0	7	6.022	9	2	6.022	0	7	6.022			
1	2	6.359	10	2	8.624	1	1	3.613	9	4	8.950	1	1	2.972	9	3	7.028	0	8	7.028	9	3	7.028	0	8	7.028			
1	3	7.589	10	3	9.857	1	2	4.777	10	0	4.486	1	2	4.047	9	4	8.005	0	9	8.005	9	4	8.005	0	9	8.005			
1	4	8.762	11	0	6.003	1	3	5.871	10	1	5.856	1	3	5.066	10	0	3.991	0	10	3.991	10	0	3.991	0	10	3.991			
1	5	9.887	11	1	7.609	1	4	6.921	10	2	7.087	1	4	6.051	10	1	5.261	0	11	5.261	10	1	5.261	0	11	5.261			
2	0	3.671	11	2	8.902	1	5	7.941	10	3	8.181	1	5	7.012	10	2	6.292	0	12	6.292	10	2	6.292	0	12	6.292			
2	1	5.200	11	3	10.133	1	6	8.938	11	0	4.830	1	6	7.955	10	3	7.294	0	13	7.294	10	3	7.294	0	13	7.294			
2	2	6.528	12	0	6.288	2	0	2.464	11	1	6.243	2	0	1.944	11	0	4.268	0	14	4.268	11	0	4.268	0	14	4.268			
2	3	7.759	12	1	7.893	2	1	3.781	11	2	7.360	2	1	3.142	11	1	5.533	0	15	5.533	11	1	5.533	0	15	5.533			
2	4	8.931	12	2	9.183	2	2	4.948	11	3	8.455	2	2	4.221	11	2	6.490	0	16	6.490	11	2	6.490	0	16	6.490			
2	5	10.060	12	3	10.410	2	3	6.044	12	0	5.111	2	3	5.242	11	3	7.559	0	17	7.559	11	3	7.559	0	17	7.559			
3	0	3.878	13	0	6.574	2	4	7.096	12	1	6.524	2	4	6.233	12	0	4.545	0	18	4.545	12	0	4.545	0	18	4.545			
3	1	5.435	13	1	8.178	2	5	8.118	12	2	7.633	2	5	7.186	12	1	5.805	0	19	5.805	12	1	5.805	0	19	5.805			
3	2	6.758	13	2	9.463	3	0	2.671	12	3	8.594	2	6	8.130	12	2	6.756	0	20	6.756	12	2	6.756	0	20	6.756			
3	3	7.981	13	3	10.687	3	1	4.001	13	0	5.392	3	0	2.151	12	3	7.825	0	21	7.825	12	3	7.825	0	21	7.825			
3	4	9.155	14	0	6.861	3	2	5.172	13	1	6.884	3	1	3.362	13	0	4.823	0	22	4.823	13	0	4.823	0	22	4.823			
3	5	10.288	14	1	8.462	3	3	6.274	13	2	7.781	3	2	4.450	13	1	6.077	0	23	6.077	13	1	6.077	0	23	6.077			
4	0	4.108	14	2	9.748	3	4	7.333	13	3	8.863	3	3	5.489	13	2	7.095	0	24	7.095	13	2	7.095	0	24	7.095			
4	1	5.656	15	0	7.148	3	5	8.368	14	0	5.607	3	4	6.444	13	3	8.091	0	25	8.091	13	3	8.091	0	25	8.091			
4	2	6.988	15	1	8.747	4	0	2.901	14	1	6.961	3	5	7.407	14	0	5.101	0	26	5.101	14	0	5.101	0	26	5.101			
4	3	8.228	15	2	10.019	4	1	4.267	14	2	8.058	4	0	2.381	14	1	6.350	0	27	6.350	14	1	6.350	0	27	6.350			
4	4	9.407	16	0	7.435	4	2	5.422	15	0	5.954	4	1	3.607	14	2	7.363	0	28	7.363	14	2	7.363	0	28	7.363			
4	5	10.545	16	1	9.031	4	3	6.537	15	1	7.237	4	2	4.668	14	3	8.230	0	29	8.230	14	3	8.230	0	29	8.230			
5	0	4.352	16	2	10.299	4	4	7.599	15	2	8.331	4	3	5.692	15	0	5.379	0	30	5.379	15	0	5.379	0	30	5.379			
5	1	5.914	17	0	7.723	4	5	8.569	16	0	6.174	4	4	6.681	15	1	6.622	0	31	6.622	15	1	6.622	0	31	6.622			
5	2	7.244	17	1	9.319	5	0	3.145	16	1	7.514	5	0	2.625	16	0	5.658	0	32	5.658	16	0	5.658	0	32	5.658			
5	3	8.489	17	2	10.579	5	1	4.549	16	2	8.729	5	1	3.865	16	1	6.895	0	33	6.895	16	1	6.895	0	33	6.895			
5	4	9.672	18	0	8.010	5	2	5.639	17	0	6.458	5	2	4.913	16	2	7.952	0	34	7.952	16	2	7.952	0	34	7.952			
5	5	10.754	18	1	9.603	5	3	6.738	17	1	7.869	5	3	5.938	17	1	7.167	0	35	7.167	17	1	7.167	0	35	7.167			
6	0	4.605	18	2	10.860	5	4	7.793	17	2	9.003	5	4	6.928	17	2	8.215	0	36	8.215	17	2	8.215	0	36	8.215			
6	1	6.182	19	0	8.298	5	5	8.815	18	0	8.143	5	5	7.894	18	0	6.216	0	37	6.216	18	0	6.216	0	37	6.216			
6	2	7.507	19	1	9.888	6	0	3.398	18	1	8.143	5	6	8.418	19	0	6.498	0	38	6.498	19	0	6.498	0	38	6.498			
6	3	8.757	20	0	8.586	6	1	4.755	19	0	7.079	6	1	4.134	19	1	7.440	0	39	7.440	19	1	7.440	0	39	7.440			
6	4	9.944	20	1	10.173	6	2	5.961	19	1	8.418	6	2	5.173	19	2	7.590	0	40	7.590	19	2	7.590	0	40	7.590			
7	0	4.864	21	0	8.874	6	3	7.000	20	0	7.369	6	3	6.197	20	0	6.777	0	41	6.777	20	0	6.777	0	41	6.777			
7	1	6.459	21	1	10.458	6	4	8.052	20	1	8.628	6	4	7.215	20	1	7.862	0	42	7.862	20	1	7.862	0	42	7.862			
7	2	7.792	22	0	9.162	6	5	9.075	21	0	7.650	6	5	8.175	21	0	7.055	0	43	7.055	21	0	7.055	0	43	7.055			
7	3	9.036	22	1	10.743	7	0	3.665	21	1	8.906	6	6	8.403	22	0	7.985	0	44	7.985	22	0	7.985	0	44	7.985			
7	4	10.217	23	0	9.450	7	1	5.035	22	0	7.932	7	0	3.168	21	1	8.133	0	45	8.133	21	1	8.133	0	45	8.133			
8	0	5.133	24	0	9.738	7	2	6.166	23	0	8.213	7	1	4.403	22	0	7.682	0	46	7.682	22	0	7.682	0	46	7.682			
8	1	6.738	25	0	10.036	7	3	7.262	24	0	8.495	7	2	5.434	23	0	7.985	0	47	7.985	23	0	7.985	0	47	7.985			
8	2	8.068	26	0	10.325	7	4	8.312	25	0	8.777	7	3	6.559	24	0	8.232	0	48	8.232	24	0	8.232	0	48	8.232			
8	3	9.307	27	0	10.613	8	0	3.936	26	0	9.058	7	4	7.478	25	0	8.232	0	49	8.232	25	0	8.232	0	49	8.232			



Table 1. (Continued)

a1 = 0.3				alpha = 0.01				a1 = 0.3				alpha = 0.05				a1 = 0.3				alpha = 0.10			
x1	x2	t(x1,x2)		x1	x2	t(x1,x2)		x1	x2	t(x1,x2)		x1	x2	t(x1,x2)		x1	x2	t(x1,x2)		x1	x2	t(x1,x2)	
0	0	3.224	7	2	7.907	0	0	2.097	7	1	5.319	0	0	1.612	6	5	8.102						
0	1	4.647	7	3	9.143	0	1	3.321	7	2	6.465	0	1	2.723	7	0	3.581						
0	2	5.884	7	4	10.206	0	2	4.407	7	3	7.427	0	2	3.726	7	1	4.761						
0	3	7.032	7	5	11.097	0	3	5.428	7	4	8.440	0	3	4.676	7	2	5.773						
0	4	8.123	8	0	5.549	0	4	6.407	7	5	9.386	0	4	5.597	7	3	6.639						
0	5	9.176	8	1	7.104	0	5	7.359	8	0	4.446	0	5	6.492	7	4	7.540						
0	6	10.199	8	2	8.257	0	6	8.290	8	1	5.751	0	6	7.373	7	5	8.260						
0	7	11.200	8	3	9.476	0	7	9.204	8	2	6.810	0	7	8.240	8	0	3.929						
1	0	3.315	8	4	10.545	1	0	2.189	8	3	7.667	1	0	1.703	8	1	5.101						
1	1	4.741	9	0	5.910	1	1	3.416	8	4	8.820	1	1	2.818	8	2	6.109						
1	2	5.979	9	1	7.465	1	2	4.504	9	0	4.801	1	2	3.823	8	3	6.965						
1	3	7.128	9	2	8.607	1	3	5.525	9	1	6.006	1	3	4.776	8	4	7.862						
1	4	8.220	9	3	9.816	1	4	6.506	9	2	6.987	1	4	5.696	9	0	4.279						
1	5	9.274	9	4	10.885	1	5	7.459	9	3	8.164	1	5	6.594	9	1	5.284						
1	6	10.298	10	0	6.273	1	6	8.390	9	4	8.953	1	6	7.475	9	2	6.413						
2	0	3.552	10	1	7.727	2	0	9.305	10	0	5.155	2	0	8.337	9	3	7.296						
2	1	4.992	10	2	8.959	2	1	2.425	10	1	6.354	2	1	1.940	9	4	8.361						
2	2	6.232	10	3	9.969	2	2	3.666	10	2	7.487	2	2	3.074	10	0	4.629						
2	3	7.386	10	4	11.248	2	3	4.765	10	3	8.341	2	3	4.096	10	1	5.625						
2	4	8.484	11	0	6.637	2	4	5.798	10	4	9.284	2	4	5.060	10	2	6.745						
2	5	9.543	11	1	8.081	2	5	6.785	11	0	5.510	2	5	5.932	10	3	7.612						
2	6	10.573	11	2	9.311	2	6	7.695	11	1	6.699	2	6	6.830	10	4	8.508						
3	0	3.840	11	3	10.332	2	7	8.627	11	2	7.825	2	7	7.711	11	0	4.982						
3	1	5.310	12	0	7.001	3	0	2.714	11	3	8.772	2	8	8.579	11	1	5.950						
3	2	6.538	12	1	8.435	3	1	3.970	12	0	5.865	3	0	2.228	11	2	7.076						
3	3	7.699	12	2	9.665	3	2	5.082	12	1	7.108	3	1	3.384	11	3	7.937						
3	4	8.804	12	3	10.675	3	3	6.044	12	2	7.999	3	2	4.340	11	4	8.672						
3	5	9.870	13	0	7.367	3	4	7.026	12	3	9.104	3	3	5.294	12	0	5.399						
3	6	10.909	13	1	8.788	3	5	8.065	13	0	6.221	3	4	6.212	12	1	6.283						
4	0	4.154	13	2	10.089	3	6	8.907	13	1	7.289	3	5	7.111	12	2	7.407						
4	1	5.663	13	3	11.018	4	0	3.027	13	2	8.502	3	6	7.992	12	3	8.184						
4	2	6.865	14	0	7.826	4	1	4.294	13	3	9.436	4	0	2.542	13	0	5.739						
4	3	8.028	14	1	9.133	4	2	5.412	14	0	6.577	4	1	3.710	13	1	6.617						
4	4	9.042	14	2	10.438	4	3	6.341	14	1	7.629	4	2	4.641	13	2	7.737						
4	5	10.097	15	0	8.186	4	4	7.322	14	2	8.861	4	3	5.590	14	0	6.079						
4	6	11.212	15	1	9.496	4	5	8.275	15	0	6.934	4	4	6.517	14	1	6.951						
5	0	4.483	15	2	10.785	4	6	9.213	15	1	8.131	4	5	7.415	14	2	8.068						
5	1	6.024	16	0	8.547	5	0	3.360	15	2	9.179	4	6	8.425	15	0	6.446						
5	2	7.214	16	1	9.850	5	1	4.637	16	0	7.387	5	0	2.892	15	1	7.284						
5	3	8.371	16	2	11.131	5	2	5.658	16	1	8.310	5	1	4.047	15	2	8.399						
5	4	9.382	17	0	8.509	5	3	6.670	16	2	9.518	5	2	4.962	16	0	6.782						
5	5	10.433	17	1	10.203	5	4	7.777	17	0	7.735	5	3	5.992	16	1	7.630						
6	0	4.837	18	0	9.270	5	5	8.728	17	1	8.852	5	4	6.898	16	2	8.573						
6	1	6.384	18	1	10.557	6	0	3.742	18	0	8.008	5	5	7.787	17	0	7.118						
6	2	7.559	19	0	9.631	6	1	4.977	18	1	8.993	5	6	8.661	17	1	7.963						
6	3	8.712	19	1	10.911	6	2	6.129	19	0	8.426	6	0	3.235	18	0	7.455						
6	4	9.714	20	0	9.994	6	3	7.148	19	1	9.333	6	1	4.427	18	1	8.296						
6	5	10.763	21	0	10.356	6	4	7.969	20	0	8.770	6	2	5.437	19	0	7.791						
7	0	5.192	22	0	10.718	6	5	9.056	21	0	9.117	6	3	6.311	20	0	8.128						
7	1	6.744	23	0	11.080	7	0	4.094	22	0	9.462	6	4	7.215	21	0	8.465						

Table 1. (Continued)

a1 = 0.35    alpha = 0.01				a1 = 0.35    alpha = 0.05				a1 = 0.35    alpha = 0.10			
x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)	x1	x2	t(x1,x2)
0	0	2.993	6	2	7.650	0	0	1.947	6	0	3.687
0	1	4.315	6	3	8.678	0	1	3.084	6	1	4.547
0	2	5.464	6	4	9.681	0	2	4.092	6	2	5.536
0	3	6.529	6	5	10.649	0	3	5.040	6	3	6.490
0	4	7.543	6	6	11.583	0	4	5.950	6	4	7.323
0	5	8.520	7	0	5.763	0	5	6.834	6	5	7.950
0	6	9.471	7	1	6.965	0	6	7.698	6	6	8.949
0	7	10.400	7	2	8.082	0	7	8.546	7	0	4.120
0	8	11.312	7	3	9.102	0	8	9.383	7	1	4.947
1	0	3.146	7	4	10.094	1	0	2.100	7	2	5.962
1	1	4.478	7	5	11.059	1	1	3.243	7	3	6.946
1	2	5.672	8	0	6.211	1	2	4.256	7	4	7.761
1	3	6.692	8	1	7.396	1	3	5.207	7	5	8.333
1	4	7.708	8	2	8.510	1	4	6.119	8	0	4.641
1	5	8.687	8	3	9.520	1	5	7.005	8	1	5.348
1	6	9.639	8	4	10.508	1	6	7.871	8	2	6.343
1	7	10.569	8	5	11.299	1	7	8.721	8	3	7.071
1	8	11.482	9	0	6.659	1	8	9.559	8	4	8.096
2	0	3.485	9	1	7.828	2	0	2.439	9	0	5.048
2	1	4.871	9	2	8.937	2	1	3.587	9	1	5.749
2	2	5.971	9	3	9.938	2	2	4.603	9	2	6.749
2	3	7.043	9	4	10.923	2	3	5.557	9	3	7.462
2	4	8.056	10	0	7.108	2	4	6.471	9	4	8.483
2	5	9.037	10	1	8.260	2	5	7.359	10	0	5.454
2	6	9.990	10	2	9.345	2	6	8.123	10	1	6.149
2	7	10.921	10	3	10.356	2	7	8.971	10	2	7.210
3	0	3.881	10	4	11.470	3	0	2.834	10	3	7.852
3	1	5.203	11	0	7.557	3	1	3.971	10	4	8.870
3	2	6.361	11	1	8.721	3	2	4.984	11	0	5.860
3	3	7.440	11	2	9.768	3	3	5.818	11	1	6.548
3	4	8.439	11	3	10.774	3	4	6.724	11	2	7.603
3	5	9.419	12	0	8.007	3	5	7.743	11	3	8.243
3	6	10.373	12	1	9.151	3	6	8.608	12	0	6.266
3	7	11.179	12	2	10.191	3	7	9.312	12	1	6.924
4	0	4.304	12	3	11.191	4	0	3.301	12	2	7.996
4	1	5.615	13	0	8.457	4	1	4.402	12	3	8.633
4	2	6.803	13	1	9.580	4	2	5.399	13	0	6.671
4	3	7.869	13	2	10.613	4	3	6.342	13	1	7.344
4	4	8.859	14	0	8.909	4	4	7.140	13	2	8.389
4	5	9.834	14	1	10.008	4	5	8.241	14	0	7.078
4	6	10.783	14	2	11.034	4	6	9.078	14	1	7.736
5	0	4.758	15	0	9.365	4	7	9.718	14	2	8.781
5	1	6.103	15	1	10.437	5	0	3.736	15	0	7.480
5	2	7.226	15	2	11.437	5	1	4.817	15	1	8.137
5	3	8.291	16	0	9.811	5	2	5.998	15	2	8.881
5	4	9.267	16	1	10.864	5	3	6.860	16	0	7.881
5	5	10.239	17	0	10.258	5	4	7.528	16	1	8.532
5	6	11.374	17	1	11.291	5	5	8.401	17	0	8.282
6	0	5.313	18	0	10.703	5	6	9.460	17	1	8.927
6	1	6.533	19	0	11.146	6	0	4.174	18	0	8.682

Table 1. (Continued)

a1 = 0.4				alpha = 0.01				a1 = 0.4				alpha = 0.05				a1 = 0.4				alpha = 0.10			
x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)
0	0	2.763	9.059	5	4	9.059	1.797	5	3	6.770	1.382	0	0	1.382	5	3	6.053						
0	1	3.983	9.926	5	5	9.926	2.846	5	4	7.580	2.334	0	1	2.334	5	4	6.792						
0	2	5.044	10.889	5	6	10.889	3.778	5	5	8.373	3.193	0	2	3.193	5	5	7.349						
0	3	6.027	5.902	6	0	5.902	4.652	5	5	9.153	4.008	0	3	4.008	5	6	8.414						
0	4	6.963	6.748	6	1	6.748	5.492	5	7	9.913	4.796	0	4	4.796	5	7	8.821						
0	5	7.865	7.943	6	2	7.943	6.308	6	0	4.737	5.565	0	5	5.565	6	0	4.213						
0	6	8.742	8.651	6	3	8.651	7.114	6	1	5.576	6.319	0	6	6.319	6	1	4.951						
0	7	9.600	9.763	6	4	9.763	7.889	6	2	6.421	7.063	0	7	7.063	6	2	5.739						
0	8	10.442	10.521	6	5	10.521	8.661	6	3	7.241	7.797	0	8	7.797	6	3	6.305						
0	9	11.270	11.370	6	6	11.370	9.423	6	4	8.047	8.524	0	9	8.524	6	4	7.564						
1	0	3.022	6.442	7	0	6.442	2.057	6	5	8.836	1.641	1	0	1.641	6	5	8.016						
1	1	4.270	7.258	7	1	7.258	3.080	6	6	9.577	2.563	1	1	2.563	6	6	9.033						
1	2	5.368	8.456	7	2	8.456	4.103	7	0	5.259	3.416	1	2	3.416	7	0	4.708						
1	3	6.258	9.370	7	3	9.370	4.876	7	1	6.065	4.228	1	3	4.228	7	1	5.427						
1	4	7.190	10.260	7	4	10.260	5.713	7	2	6.899	5.014	1	4	5.014	7	2	6.446						
1	5	8.090	11.006	7	5	11.006	6.528	7	3	7.712	5.782	1	5	5.782	7	3	6.973						
1	6	8.966	11.703	7	6	11.703	7.324	7	4	8.523	6.535	1	6	6.535	7	4	7.796						
1	7	9.822	6.980	8	0	6.980	8.107	7	5	9.301	7.277	1	7	7.277	7	5	8.251						
1	8	10.663	7.797	8	1	7.797	8.878	8	0	5.774	8.011	1	8	8.011	8	0	5.198						
1	9	11.491	8.967	8	2	8.967	9.640	8	1	6.552	8.737	1	9	8.737	8	1	5.891						
2	0	3.514	9.646	8	3	9.646	2.549	8	2	7.377	2.133	2	0	2.133	8	2	6.833						
2	1	4.784	10.635	8	4	10.635	3.503	8	3	8.183	2.974	2	1	2.974	8	3	7.216						
2	2	5.843	11.490	8	5	11.490	4.415	8	4	8.983	3.818	2	2	3.818	8	4	8.467						
2	3	6.675	7.519	9	0	7.519	5.282	8	5	9.751	4.626	2	3	4.626	8	5	8.702						
2	4	7.604	8.317	9	1	8.317	6.118	9	0	6.282	5.409	2	4	5.409	9	0	5.682						
2	5	8.502	9.248	9	2	9.248	6.932	9	1	7.037	6.175	2	5	6.175	9	1	6.148						
2	6	9.376	10.145	9	3	10.145	7.728	9	2	7.854	6.927	2	6	6.927	9	2	7.386						
2	7	10.227	11.126	9	4	11.126	8.502	9	3	8.653	7.668	2	7	7.668	9	3	7.674						
2	8	11.072	8.058	10	0	8.058	9.272	9	4	9.615	8.358	2	8	8.358	9	4	8.878						
3	0	4.077	8.835	10	1	8.835	10.033	10	0	6.785	9.127	2	9	9.127	9	5	9.153						
3	1	5.169	9.986	10	2	9.986	3.158	10	1	7.521	2.681	3	0	2.681	10	0	6.282						
3	2	6.394	10.751	10	3	10.751	3.982	10	2	8.330	3.532	3	1	3.532	10	1	6.615						
3	3	7.287	11.784	10	4	11.784	5.086	10	3	9.123	4.352	3	2	4.352	10	2	7.889						
3	4	8.193	8.596	11	0	8.596	5.831	10	4	9.985	5.144	3	3	5.144	10	3	8.131						
3	5	9.169	9.476	11	1	9.476	6.651	11	0	7.283	5.917	3	4	5.917	11	0	6.752						
3	6	10.038	10.370	11	2	10.370	7.452	11	1	8.002	6.672	3	5	6.672	11	1	7.080						
3	7	10.780	11.248	11	3	11.248	8.238	11	2	8.804	7.485	3	6	7.485	11	2	8.301						
3	8	11.611	9.128	12	0	9.128	9.013	11	3	9.397	8.154	3	7	8.154	11	3	8.587						
4	0	4.655	9.863	12	1	9.863	9.778	12	0	7.777	8.948	3	8	8.948	12	0	7.236						
4	1	5.687	10.868	12	2	10.868	3.679	12	1	8.482	3.197	4	0	3.197	12	1	7.539						
4	2	6.909	11.634	12	3	11.634	4.581	12	2	9.524	3.996	4	1	3.996	12	2	8.758						
4	3	7.760	9.656	13	0	9.656	5.450	12	3	9.868	4.814	4	2	4.814	12	3	9.042						
4	4	8.773	10.489	13	1	10.489	6.289	13	0	8.267	5.598	4	3	5.598	13	0	7.701						
4	5	9.539	11.365	13	2	11.365	7.104	13	1	8.960	6.510	4	4	6.510	13	1	8.005						
4	6	10.397	10.178	14	0	10.178	7.911	13	2	10.059	7.117	4	5	7.117	13	2	9.213						
4	7	11.239	10.992	14	1	10.992	8.694	14	0	8.755	7.865	4	6	7.865	14	0	8.163						
5	0	5.325	10.697	15	0	10.697	9.461	14	1	9.229	8.593	4	7	8.593	14	1	8.460						
5	1	6.210	11.497	15	1	11.497	4.209	15	0	9.357	3.710	5	0	3.710	15	0	8.624						
5	2	7.428	11.212	16	0	11.212	4.971	15	1	9.703	4.478	5	1	4.478	15	1	8.925						
5	3	8.277	11.724	17	0	11.724	5.942	16	0	9.833	5.276	5	2	5.276	16	0	9.084						

Table 1. (Continued)

a1 = 0.45				alpha = 0.01				a1 = 0.45				alpha = 0.05				a1 = 0.45				alpha = 0.10			
x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)	x1	x2	t(x1,x2)	t(x1,x2)
0	0	2.533	7 10.825	4	4	1.648	0 0	0	0	1.648	4 6	4	4	8.441	0 0	0	0	1.266	4 6	4	4	6 7.795	
0	1	3.651	8 11.574	4	4	2.609	0 1	0	1	2.609	4 7	4	4	9.139	0 1	0	1	2.139	4 7	4	4	7 8.490	
0	2	4.623	5 0 5.899	4	3	3.490	0 2	0	2	3.490	4 8	4	4	9.829	0 2	0	2	2.964	4 8	4	4	8 9.116	
0	3	5.525	5 1 6.666	4	4	4.264	0 3	0	3	4.264	5 0	5	0	8.09	0 3	0	3	3.674	5 0	5	0	4 4.233	
0	4	6.382	5 2 7.491	4	5	5.034	0 4	0	4	5.034	5 1	5	1	5.270	0 4	0	4	4.419	5 1	5	1	1 4.540	
0	5	7.217	5 3 8.300	4	6	5.782	0 5	0	5	5.782	5 2	5	2	6.124	0 5	0	5	5.101	5 2	5	2	2 5.470	
0	6	8.014	5 4 9.107	4	7	6.513	0 6	0	6	6.513	5 3	5	3	6.848	0 6	0	6	5.793	5 3	5	3	3 6.152	
0	7	8.800	5 5 9.870	4	8	7.232	0 7	0	7	7.232	5 4	5	4	7.591	0 7	0	7	6.474	5 4	5	4	4 6.856	
0	8	9.571	5 6 10.634	4	9	7.939	0 8	0	8	7.939	5 5	5	5	8.283	0 8	0	8	7.147	5 5	5	5	5 7.505	
0	9	10.331	5 7 11.387	4	10	8.656	0 9	0	9	8.656	5 6	5	6	8.984	0 9	0	9	7.813	5 6	5	6	6 8.173	
0	10	11.092	6 0 6.557	4	11	9.329	0 10	0	10	9.329	5 7	5	7	9.677	0 10	0	10	8.474	5 7	5	7	7 8.834	
0	11	11.833	6 1 7.129	4	12	10.033	0 11	0	11	10.033	6 0	6	0	5.397	0 11	0	11	9.129	6 0	6	0	4 4.791	
1	0	3.021	6 2 8.099	4	1	2.135	1 0	1	0	2.135	6 1	6	1	5.843	1 0	1	0	1.750	6 1	6	1	1 5.198	
1	1	4.073	6 3 8.894	4	2	3.011	1 1	1	1	3.011	6 2	6	2	6.692	1 1	1	1	2.528	6 2	6	2	2 6.010	
1	2	5.020	6 4 9.693	4	3	3.839	1 2	1	2	3.839	6 3	6	3	7.409	1 2	1	2	3.290	6 3	6	3	3 6.685	
1	3	5.908	6 5 10.444	4	4	4.626	1 3	1	3	4.626	6 4	6	4	8.141	1 3	1	3	4.024	6 4	6	4	4 7.385	
1	4	6.757	6 6 11.180	4	5	5.391	1 4	1	4	5.391	6 5	6	5	8.672	1 4	1	4	4.742	6 5	6	5	5 8.027	
1	5	7.578	6 7 11.929	4	6	6.134	1 5	1	5	6.134	6 6	6	6	9.521	1 5	1	5	5.437	6 6	6	6	6 8.691	
1	6	8.377	6 8 12.688	4	7	6.861	1 6	1	6	6.861	6 7	6	7	10.055	1 6	1	6	6.124	6 7	6	7	0 5.344	
1	7	9.160	7 1 7.803	4	8	7.569	1 7	1	7	7.569	6 8	6	8	5.977	1 7	1	7	6.802	6 8	6	8	1 5.703	
1	8	9.928	7 2 8.721	4	9	8.273	1 8	1	8	8.273	7 1	7	1	6.371	1 8	1	8	7.472	7 1	7	2	2 6.547	
1	9	10.685	7 3 9.506	4	10	8.969	1 9	1	9	8.969	7 2	7	2	7.252	1 9	1	9	8.136	7 2	7	3	3 7.055	
1	10	11.432	7 4 10.286	4	11	9.659	1 10	1	10	9.659	7 3	7	3	7.961	1 10	1	10	8.794	7 3	7	4	4 7.913	
2	0	3.783	7 5 11.016	4	12	2.833	2 0	2	0	2.833	7 4	7	4	8.825	2 0	2	0	2.395	7 4	7	5	5 8.391	
2	1	4.725	7 6 11.773	4	1	3.411	2 1	2	1	3.411	7 5	7	5	9.365	2 1	2	1	2.887	7 5	7	6	6 9.207	
2	2	5.633	8 0 7.916	4	2	4.05	2 2	2	2	4.05	8 0	8	0	6.550	2 2	2	2	3.436	8 0	8	0	0 5.891	
2	3	6.496	8 1 8.410	4	3	4.732	2 3	2	3	5.173	8 1	8	1	6.974	2 3	2	3	4.260	8 1	8	1	1 6.279	
2	4	7.141	8 2 9.312	4	4	5.330	2 4	2	4	5.930	8 2	8	2	7.809	2 4	2	4	5.260	8 2	8	2	2 7.215	
2	5	8.145	8 3 10.090	4	5	6.053	2 5	2	5	6.553	8 3	8	3	8.510	2 5	2	5	5.940	8 3	8	3	3 7.736	
2	6	8.936	8 4 10.866	4	6	6.732	2 6	2	6	7.372	8 4	8	4	9.234	2 6	2	6	6.622	8 4	8	4	4 8.547	
2	7	9.712	8 5 11.613	4	7	7.405	2 7	2	7	8.080	8 5	8	5	9.903	2 7	2	7	7.295	8 5	8	5	5 8.943	
2	8	10.476	9 0 8.530	4	8	8.089	2 8	2	8	8.589	9 0	9	0	7.118	2 8	2	8	7.961	9 0	9	0	0 6.432	
2	9	11.021	9 1 9.011	4	9	8.722	2 9	2	9	9.472	9 1	9	1	7.533	2 9	2	9	8.622	9 1	9	0	1 6.814	
2	10	11.759	9 2 9.902	4	10	9.469	2 10	2	10	9.969	9 2	9	2	8.362	2 10	2	10	9.277	9 2	9	1	2 7.611	
3	0	4.520	9 3 10.672	4	11	3.611	3 0	3	0	3.611	9 3	9	3	9.056	3 0	3	0	3.097	9 3	9	2	3 8.267	
3	1	5.375	9 4 11.443	4	12	4.067	3 1	3	1	4.067	9 4	9	4	9.776	3 1	3	1	3.511	9 4	9	3	4 9.057	
3	2	6.247	10 0 9.137	4	1	4.975	3 2	3	2	4.975	10 0	10	0	7.680	3 2	3	2	4.651	10 0	10	0	0 6.971	
3	3	7.334	10 1 9.607	4	2	5.724	3 3	3	3	5.724	10 1	10	1	8.087	3 3	3	3	5.074	10 1	10	0	1 7.345	
3	4	7.918	10 2 10.490	4	3	6.325	3 4	3	4	6.325	10 2	10	2	8.911	3 4	3	4	5.628	10 2	10	2	2 8.139	
3	5	8.700	10 3 11.251	4	4	7.183	3 5	3	5	7.183	10 3	10	3	9.599	3 5	3	5	6.314	10 3	10	3	3 8.789	
3	6	9.480	11 0 9.737	4	5	7.895	3 6	3	6	7.895	10 4	10	4	10.129	3 6	3	6	6.990	11 0	11	0	0 7.505	
3	7	10.246	11 1 10.197	4	6	8.795	3 7	3	7	8.795	11 0	11	0	8.238	3 7	3	7	7.659	11 1	11	1	1 7.874	
3	8	11.229	11 2 11.074	4	7	9.293	3 8	3	8	9.293	11 1	11	1	8.638	3 8	3	8	8.322	11 1	11	2	2 8.665	
4	0	5.222	11 3 11.826	4	8	10.174	3 9	3	9	10.174	11 2	11	2	9.457	3 9	3	9	8.982	11 2	11	3	3 9.310	
4	1	6.028	12 0 10.331	4	9	4.211	4 0	4	0	4.211	12 0	12	0	8.791	4 0	4	0	3.666	12 0	12	0	0 8.036	
4	2	6.878	12 1 10.783	4	10	4.689	4 1	4	1	4.689	12 1	12	1	9.185	4 1	4	1	4.099	12 1	12	1	1 8.407	
4	3	7.703	12 2 11.654	4	11	5.555	4 2	4	2	5.555	12 2	12	2	10.001	4 2	4	2	4.925	12 2	12	2	2 9.188	
4	4	8.518	13 0 10.921	4	12	6.478	4 3	4	3	6.478	13 0	13	0	9.341	4 3	4	3	5.788	13 0	13	0	0 8.564	
4	5	9.293	13 1 11.365	4	13	7.037	4 4	4	4	7.037	13 1	13	1	9.730	4 4	4	4	6.450	13 1	13	1	1 8.924	
4	6	10.065	14 0 11.506	4	14	7.735	4 5	4	5	7.735	14 0	14	0	9.887	4 5	4	5	7.156	14 0	14	0	0 9.089	

A somewhat more complicated case making use of the possibility of combining component data when some sample sizes are equal, as described in Section 1, is illustrated by

Example 2. Consider a five-component series system with test data  $X_1 = 0, X_2 = 4, X_3 = 2, X_4 = 1, X_5 = 3$ , based on corresponding sample sizes  $n_1 = n_2 = n_3 = 300, n_4 = n_5 = 200$ . Here  $c = (3/300 + 2/200) = .02, a_1 = a_2 = a_3 = 1/300(.02) = 1.6, a_4 = a_5 = 1/200(.02) = 1/4$ . For the equivalent  $k^* = 2$  problem we divide the two distinct values of the  $a_i$ 's by their sum  $c_0 = 1/6 + 1/4 = 5/12$ , obtaining  $a_1^* = .40, a_2^* = .60$ . The corresponding numbers of failures are  $X_1^* = X_1 + X_2 + X_3 = 6$  and  $X_2^* = X_4 + X_5 = 4$ . For the reduced problem we consult Table 1 for  $\alpha = .10$  to find the 90 percent confidence bound 7.564. This must be multiplied by  $c_0$  to obtain the bound for the original  $\theta(\lambda)$ . The 90 percent lower bound  $r(x)$  for the system reliability given by (1.6) thus becomes  $1 - cc_0 t(x) = 1 - (.02)(5/12)(7.564) = .937$ .

If the observed numbers of failures fall outside the limits of Table 1, the approximate methods discussed in the next section may be employed.

#### 4. Approximations

In this section approximate confidence bounds for systems with more than two components having distinct sample sizes are developed. The use of the maximum likelihood ratio confidence bound for cases falling outside the scope of Table 1 is also discussed.

For  $k > 2$  it is impractical to generate the optimal ordering and the corresponding values of the upper confidence bound for more than a few illustrative cases. Thus, some method of approximating solutions for  $k > 2$  with acceptable precision is required. The approach to be followed here is to find a  $k = 2$  problem which is sufficiently similar in structure to the given  $k > 2$  problem so that the confidence bounds for the two problems are essentially the same except for a normalizing factor. This method may be thought of as an extension and refinement of the Lindstrom-Madden procedure (see Lloyd and Lipow 1977, and cf. Harris and Soms 1980).

The Lindstrom-Madden method first estimates the reliability by maximum likelihood and then uses the  $k = 1$  confidence bound solution for the component with the smallest sample size and a fictitious number of failures determined so as to reproduce the estimated system reliability. The procedure proposed here is to estimate two quantities, the value of  $\theta$  and the variance of the maximum likelihood estimate of  $\theta$ , and to use these estimates to find a  $k = 2$  problem based on two of the original  $a_i$ 's with a pair of corresponding fictitious observation values chosen to reproduce the estimated quantities. The two  $a_i$ 's are chosen to be as large as possible (corresponding to sample sizes as small as possible) subject to two constraints. The

first constraint guarantees that the resulting fictitious observations are non-negative. The second constraint requires that  $a_i$ 's corresponding to zero failures in the original problem not be considered unless all but one of the components have zero failures. These considerations lead to a unique  $k = 2$  problem whose solution provides a very good approximation to the solution for the original  $k > 2$  problem.

The elimination of  $a_i$ 's for components exhibiting zero failures is justified by the fact that the maximum likelihood ratio confidence bound (discussed later) is invariant under such transformations. That is, if the dimension  $k$  is reduced by the elimination of all  $a_i$ 's corresponding to zero failures, then the value of the maximum likelihood ratio bound remains unchanged.

The choice of the two quantities whose estimates are used to determine the pair of fictitious observations is supported by analogy with Lindstrom-Madden (in the case of  $\theta$ ) and by the fact that the two estimates are the ingredients of the asymptotic maximum likelihood ratio confidence bound thereby insuring asymptotic optimality. The details of the approximation algorithm are as follows:

(a) First  $\theta(\lambda) = \sum_{i=1}^k a_i \lambda_i$  is estimated by

$$\hat{\theta} = \sum_{i=1}^k a_i X_i, \quad (4.1)$$

and the quantity  $\text{Var}(\hat{\theta}) = \sum_{i=1}^k a_i^2 \lambda_i$  is estimated by

$$\hat{v} = \sum_{i=1}^k a_i^2 X_i. \quad (4.2)$$



(b) Next if at least one component exhibits one or more failures, the pair  $(a_i, a_j)$ ,  $i < j$ , is selected so that

$$(i) \quad a_i \leq \hat{v}/\hat{\theta} \quad , \quad \text{and}$$

$$(ii) \quad a_j \geq \hat{v}/\hat{\theta} \quad .$$

Subject to these conditions,  $a_i$  and  $a_j$  are taken to be the largest available values associated with at least one failure. If all  $a_i$ 's satisfying (i) correspond to zero failures, then  $a_i$  is taken to be the largest in that group. If all the  $a_j$ 's satisfying (ii) correspond to zero failures, then  $a_j$  is taken to be  $a_k$ . If all components exhibit zero failures,  $\hat{v}/\hat{\theta}$  is indeterminate and  $a_i$  and  $a_j$  are taken to be  $a_1$  and  $a_k$  respectively.<sup>1</sup>

(c) The pseudo-observations  $x_1^*$  and  $x_2^*$  are computed by the formulae

$$x_1^* = \frac{a_j \hat{\theta} - \hat{v}}{a_i (a_j - a_i)} \quad , \quad (4.3)$$

$$x_2^* = \frac{\hat{v} - a_i \hat{\theta}}{a_j (a_j - a_i)} \quad .$$

These values will be non-negative by conditions (i) and (ii) of (b), and when associated with  $a_i$  and  $a_j$  respectively they

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<sup>1</sup>For this case the resulting confidence bound is exact and is the same as would be obtained by multiplying  $a_k$  times the upper confidence bound for a single Poisson parameter when zero failures are observed, i.e.,  $t(0) = a_k \log (1/\alpha)$ .

reproduce the values of  $\hat{\theta}$  and  $\hat{v}$  provided all other observations are replaced by zeros.

- (d) The  $k = 2$  problem with  $x_1^*$  and  $x_2^*$  associated with  $a_1^* = a_i/(a_i + a_j)$  and  $a_2^* = a_j/(a_i + a_j)$  respectively may now be treated using Table 1 to yield  $t(x_1^*, x_2^*)$ . Since  $x_1^*$  and  $x_2^*$  are not necessarily integers, it may be necessary to interpolate with respect to these arguments as well as the value of  $a_1 = a_1^*$ .

- (e) The approximate upper confidence bound  $t^*$  for  $\theta$  for the original  $k > 2$  problem is then given by

$$t^*(x) = (a_i + a_j)t(x_1^*, x_2^*) \quad . \quad (4.4)$$

In order to check the validity of this approximation algorithm, the confidence bounds for the first 24 points in the optimal (two-stage prospective) ordering were computed for a typical  $k = 3$  case. These results were obtained by a rather laborious method based on formula (2.7) and involving repeated interactive searches of the  $(\lambda_1, \lambda_2, \lambda_3)$  simplex. The approximation algorithm was applied to each of these points and the comparative results are shown in Table 2. The values of  $a_1$ ,  $a_2$ , and  $a_3$  for this example were chosen to be of roughly the same magnitude but not so close that the combination of any two would be indicated.

To check the algorithm for cases farther from the origin several additional examples were considered using a somewhat different method which avoids the necessity for sequentially generating the

Table 2. The Performance of the Approximation Algorithm for the First 24 Ordered Points for a Typical Example With  $k = 3$ .

$\alpha = .05; a_1 = .2, a_2 = .3, a_3 = .5$						
Two-Step Prospective Sequential					Approximation Algorithm	Relative Error
$n$	$x_1$	$x_2$	$x_3$	$t(x)$	$t^*(x)$	
1	0	0	0	1.498	1.498	+ 00.0 %
2	1	0	0	1.553	1.555	+ 00.1
3	0	1	0	1.656	1.663	+ 00.4
4	2	0	0	1.703	1.705	+ 00.2
5	1	1	0	1.756	1.540	- 12.3
6	2	1	0	1.861	1.752	- 05.9
7	3	0	0	1.933	1.891	- 02.1
8	0	2	0	1.981	1.995	+ 00.7
9	1	2	0	2.085	2.052	- 01.6
10	4	0	0	2.088	2.094	+ 00.3
11	3	1	0	2.162	1.991	- 07.9
12	2	2	0	2.268	2.208	- 02.7
13	5	0	0	2.300	2.309	+ 00.4
14	0	3	0	2.354	2.397	+ 01.8
15	0	0	1	2.372	2.372	+ 00.0
16	4	1	0	2.382	2.291	- 03.9
17	1	0	1	2.429	2.431	+ 00.1
18	1	3	0	2.472	2.438	- 01.4
19	5	1	0	2.504	2.486	- 00.7
20	0	1	1	2.543	2.529	- 00.5
21	6	0	0	2.575	2.551	- 01.0
22	2	0	1	2.602	2.589	- 00.8
23	2	3	0	2.609	2.641	+ 01.2
24	1	1	1	2.660	2.668	+ 00.3

optimal ordering of the sample points. For these examples the ordering was generated by the values of the maximum likelihood ratio confidence bounds (see below) associated with the sample points. Since this ordering is asymptotically optimal (for large  $\lambda_i$ 's), it can be expected to produce good results for sample points well removed from the origin. The values of the confidence bounds calculated using (2.7) and the approximations obtained by the proposed algorithm are shown for these examples in Table 3.

In Table 3 the tendency of the computed values of  $t(x)$  to be slightly larger than the algorithm values may be due to the fact that the ordering used to compute the former is non-optimal. Formal application of the algorithm may occasionally result in the selection of nearly equal values  $a_i$  and  $a_j$  in step (b). When this happens, improved results may be obtained by first reducing the dimension  $k$  by combining the nearly equal  $a_i$ 's and then applying the algorithm. This method was used for the two cases in Table 3 marked by (+). The algorithm values for all cases where  $a = (.14, .16, .70)$  or  $a = (.15, .41, .44)$  do not differ substantially from the values which would be obtained by reducing to the  $k = 2$  case by combining the nearly equal  $a_i$ 's. Similarly, the values for the cases where  $a = (.32, .33, .35)$  can be nearly reproduced by multiplying the  $k = 1$  bound by  $\bar{a} = .333$ .

The number of sample points appearing in the ordering before a given level of  $t(x)$  is reached increases rapidly as  $k$  increases.

Table 3. Several Examples Comparing the Algorithm Values With the Exact Bounds Based on the Ordering Generated by the m&rb.

$\alpha = .05$							
$a_1$	$a_2$	$a_3$	$x_1$ $x_2$ $x_3$	Position in Ordering	$t(x)$	Algorithm Value $t^*(x)$	m&rb
.20, .30, .50			2, 2, 1	50	3.329	3.273	3.070
			5, 0, 2	100	4.068	3.957	3.798
			6, 6, 0	200	4.887	4.789	4.708
			9, 1, 3	400	5.980	5.892	5.795
.14, .16, .70			5, 4, 0	50	3.026	3.084 <sup>†</sup>	2.218
			2, 10, 0	100	3.424	3.531 <sup>†</sup>	2.921
			2, 5, 1	200	4.407	4.086	3.729
.15, .41, .44			13, 0, 0	50	3.245	3.223	2.980
			5, 2, 1	100	4.028	3.860	3.699
			3, 3, 2	200	4.861	4.738	4.559
.32, .33, .35			0, 3, 2	50	3.492	3.518	3.256
			1, 5, 1	100	4.339	4.332	4.076
			1, 5, 3	200	5.198	5.234	4.993

<sup>†</sup> Reduction to  $k=2$  case by combining  $a_1$  and  $a_2$ .

Hence for  $k > 2$  the algorithm may be applied to sample points positioned quite far along in the ordering without requiring values beyond the scope of Table 1, as is seen in the examples of Table 3.

The results detailed in Tables 2 and 3 suggest that the application of the proposed algorithm together with the combining of nearly equal  $a_i$ 's when indicated will nearly always produce confidence bounds for  $\theta(\lambda)$  subject to relative errors not exceeding 10 percent and often much less. Furthermore, the lower confidence bound for reliability  $r(x)$  given by (1.6) will exhibit a much smaller relative error since the relative error in approximations for  $t(x)$  applies only to the difference between the lower bound and one; a quantity which at worst is of the order of  $1/10$  in the contemplated applications.

In situations where very large sample sizes are available, it may happen that the observed numbers of failures exceed the limits of Table 1 even though the system reliability is high. For such cases the maximum likelihood ratio bound (mlrb) may be used. This approximate confidence bound is obtained in the usual way from the maximum likelihood ratio statistic for testing the hypothesis  $H_0 : \theta(\lambda) = \theta_0$  versus all alternatives. The corresponding one-sided confidence bound may be shown (see Johns 1975) to be determined as follows: Let  $\hat{\mu}$  be the positive real root less than  $1/(\text{largest } a_i \text{ for which } X_i > 0)$  of the equation

$$\chi_{1,2\alpha}^2 = 2 \sum_{i=1}^k X_i \left\{ \frac{a_i \hat{\mu}}{1 - a_i \hat{\mu}} + \log(1 - a_i \hat{\mu}) \right\}, \quad (4.5)$$

where  $\chi_{1,2\alpha}^2$  is the upper  $100(2\alpha)$ -th percentage point of the chi-squared distribution with one degree of freedom. Then the quantity

$$\hat{t}(X) = \sum_{i=1}^k a_i X_i / (1 - a_i \hat{\mu}) \quad (4.6)$$

is the approximate upper  $1 - \alpha$  level confidence bound for  $\theta(\underline{\lambda})$ . As  $\max(\lambda_1, \lambda_2, \dots, \lambda_n) \rightarrow \infty$ , the mlrb  $\hat{t}(X)$  may be shown (see Johns 1975) to be asymptotically equivalent to

$$\tilde{t}(X) = \sum_{i=1}^k a_i X_i + z_\alpha \left( \sum_{i=1}^k a_i^2 X_i \right)^{1/2}, \quad (4.7)$$

where  $z_\alpha$  is the  $100\alpha$ -th percentage point of the standard normal distribution.

Neither of these approximate bounds is useful for sample points near the origin in the usual orderings, but  $\hat{t}$  given by (4.6) becomes sufficiently precise for application to sample points beyond the scope of Table 1. A comparison of  $t(x_1, x_2)$  and the corresponding mlrb for the last (i.e., the 100-th) points in each of the optimal orderings for the cases covered in Table 1 is given in Table 4.

Table 4.  $m\ellrb/t(x_1, x_2)$  for the 100-th Point in Each Ordering

$\alpha$	$a_1$								
	.05	.10	.15	.20	.25	.30	.35	.40	.45
.01	.62	.95	.97	.97	.98	.97	.98	.97	.99
.05	.72	.88	.96	.95	.98	.97	.99	.95	.96
.10	.89	.95	.95	.96	.97	1.00	.97	.96	.98

These results suggest that the  $m\ellrb$  possesses satisfactory precision for sample points beyond those listed in Table 1 for  $k = 2$  whenever  $a_1 \geq .10$ . The last column of Table 3 giving the  $m\ellrb$  values for the examples considered illustrates the fact that for  $k > 2$  the  $m\ellrb$  tends to underestimate the correct value of the bound for sample points within the range that can be dealt with using Table 1 and the algorithm.

Two potential sources of error for the lower confidence bound on system reliability remain to be discussed. They are (i) the Poisson approximation to the binomial distribution of the observed failures, and (ii) the approximation for reliability given in (1.2) and reflected in the formula (1.6) for the lower bound  $r(x)$ . It is intuitively clear from (1.1) ff. that the "worst case" for the Poisson approximation should occur when  $k = 1$ ; since to match a given  $k = 1$  level of reliability, say  $1 - p$ , by a  $k > 1$  case, we must have  $p \approx \sum_{i=1}^k p_i$ , so that the  $p_i$ 's must be smaller than  $p$  which tends to improve the Poisson approximation.



For the case  $k = 1$  the familiar upper confidence bounds for a single Poisson parameter apply and the actual coverage probabilities for the proposed method (3.1) can be computed for any  $n$  and  $p$  from tables of the binomial distribution. The results of several such calculations are shown in Table 5.

Table 5. "Worst Case" Analysis ( $k=1$ ). Minimum Coverage Probabilities for  $r(x)$ .

Reliability $q = 1 - p$	$1 - \alpha$		
	.90	.95	.99
.95	.906	.954	.991
.90	.912	.958	.992
.80	.924	.965	.995
.70	.936	.972	.997

These values suggest that the approximations operate to make the proposed confidence bounds slightly conservative. It is interesting to observe that the minimum coverage probabilities are not drastically different from the nominal values, even for a true reliability as low as .70.

## 5. Acknowledgments and Remarks Concerning the Computations

The computations for Table 1 were performed on a Digital Equipment PDP-11/34 running under a UNIX operating system. The production program for these computations (506 lines) was written in the "C" language by the author. The method used for the

computation of the upper bounds was an implementation of (2.7); and as has been noted, the sample points were ordered by the two-step prospective sequential method. The tabled results were subjected to various checks to insure that the correct global maxima were found in each case.

The computations involved in obtaining the one-step look-ahead results and the tree analysis associated with the semi-Bayesian results discussed in Section 3 were done on an IBM 370/168 machine using Fortran programs developed by David Pasta. These programs compute the upper bounds by a somewhat more complicated method used in the earlier phases of the study and detailed in Johns (1975).

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generated sequentially by a two-stage, prospective optimization procedure. A generalization of the Lindstrom-Madden technique is proposed for using the tables to find confidence bounds for systems consisting of more than two components with differing sample sizes.